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GRAVITY OBSERVATIONS IN THE WRIGHT VALLEY AREA, VICTORIA LAND, ANTARCTICA

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Summary

Measurements of the acceleration due to gravity have been made in the Wright Valley area of Victoria Land, Antarctica. On an east-west traverse from the coast of McMurdo Sound, across the Wilson Piedmont and Lower Wright Glaciers and along the Wright Valley the Bouguer anomaly varies from − 10 mgal at the coast to − 80 mgal at the western edge of the Lower Wright Glacier and to − 110 mgal at the head of the valley. The gradient near the coast is about 5 mgal/km; along the valley it is about 1 mgal/km.

INTRODUCTION

Measurements of the acceleration due to gravity were made by members of the Victoria University of Wellington Antarctic Expedition, 1958–9, on a traverse from the coast of McMurdo Sound near Marble Point, across the Wilson Piedmont Glacier and the Lower Wright Glacier. The traverse was extended as far westwards along the Wright Valley towards the inland ice plateau as was possible in the time available. (See Figs. 1 and 2.)

The limited value of gravity readings along a single line is appreciated. However, other measurements of gravity, at isolated stations and along traverses, have been made in the Ross Dependency and further gravity surveys are included in the plans of forthcoming expeditions. The results in the Wright Valley area thus form part of the regional cover.

DESCRIPTION OF THE AREA

In the area of this survey the western coast of McMurdo Sound runs approximately north-south. The Wilson Piedmont Glacier extends inland from the coast for distances varying between 10 and 25 km. The maximum

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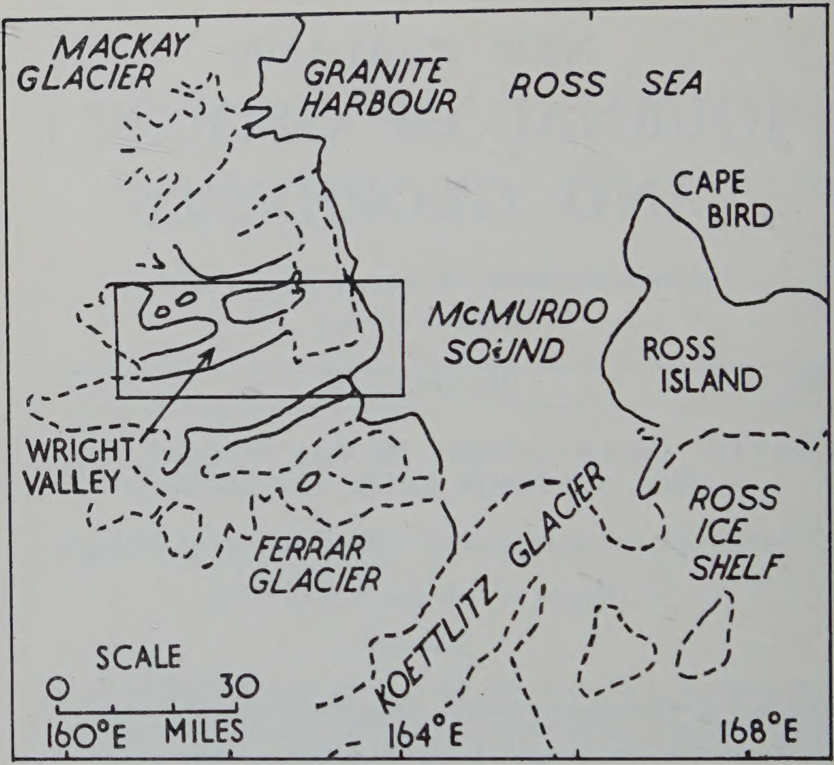

FIG. 1—Locality Map of Wright Valley area.

altitude of the Piedmont Glacier is about 700 m. West of the Wilson Piedmont Glacier is an ice-free area of about 4,000 sq. km. This is an elevated area of continental type rocks transected by deep east-west valleys. The basement rock of the area consists of older granites, gneisses, schists and marbles, overlain by a "pink" granite. The basement is overlain by Beacon Group sediments more than 1,500 m in thickness. Widescale intrusions of dolerites occur within the basement and sediments; two dolerite sheets below the sediments vary in thickness from 250 to 600 m. The altitude of the upland areas increases from about 1,300 m in the east, to about 2,700 m in the west, where the land merges with the inland ice plateau of eastern Antarctica.

The major east-west valleys are the Wright Valley in the south and the Victoria Valley further north. These are glacier-cut valleys but the central portions of the glaciers have disappeared, leaving only small remnants at the upper and lower ends of the valleys.

The Wright Valley is about 50 km long and varies in width from 3 to 5 km. Its longitudinal profile is shown in Fig. 3A. The western end is occupied by the Upper Wright Glacier, which lies at an altitude of about 1,400 m. For most of its length, the valley floor is at an altitude of less than 400 m. The lowest part of the valley is occupied by Lake Vanda, the ice-covered surface of which is 143 m above sea-level. The Lower Wright Glacier, at the eastern end of the valley, is now merely a lobe of the Wilson Piedmont Glacier.

THE GRAVITY TRAVERSE

The instrument used was a Worden Gravity Meter, W 283, belonging to Geophysics Division, Department of Scientific and Industrial Research, Wellington.

The principal gravity base for the Pacific side of the Antarctic continent is the Gulf Pendulum station at U.S. Navy Air Facility, McMurdo Sound (77° 53′ 7″ S., 166° 45′ 18″ E.) (Thiel *et al.,* 1959). The value of the acceleration due to gravity there is based on the accepted value in Washington, U.S.A. Gravity stations at Scott Base (77° 51′ 30″ S., 166° 47′ E.) have been established by gravimeter linkages with the Gulf Pendulum station. Relative to the Washington value, the value of gravity at Scott Base is probably accurate to ± 1 mgal.

The Worden meter was read at a Scott Base gravity station on 19 December 1958 and flown to the Expedition's Main Base near the eastern end of Lake Vanda, where it was read on 21 December. This pair of readings constitutes one linkage. At the end of the Expedition the meter was read regularly over a 3-day period at Main Base, and then for 4 days at Scott Base, the interval between the Main Base and Scott Base readings being 5 hours. These readings constitute a second and more reliable linkage.

A satisfactory check on the calibration of the meter was provided by a linkage with the established gravity station at the U.S. Navy Air Facility, Marble Point, on the McMurdo Sound Coast. Early in 1958 Ostenso determined the value of gravity at Marble Point as 982,951·3 mgal, by direct linkages with the Gulf Pendulum station. (Thiel *et al.,* 1959). In the present work the value of gravity obtained at Main Base by the two linkages with Scott Base has been taken as correct. The figure used for the sensitivity of the instrument is the mean of the values obtained in New Zealand before and after the Antarctic summer work. (Mr W. I. Reilly, pers. comm.) Using this value for the sensitivity, the value of gravity we obtain at the U.S. Marble Point gravity station is 982,951·2 mgal, which differs from Ostenso's value by only 0·1 mgal.

Seventy-six gravity stations were made at intervals of between 0·5 and 2·0 km along the 85 km traverse (see Fig. 1). Normally closed loops of 6 or 7 stations were made but across the Lower Wright and Wilson Piedmont Glaciers readings were made only on the eastward journey. The drift of the meter was small and steady during the Expedition, the total drift being only 4·9 mgal in 47 days. Correcting for this drift, the remaining closure error at station 31 after the double crossing of the glaciers is 0·6 mgal.

Enough of the survey data of the Expedition has been worked up to allow adequate correction of the existing sketch map of the area. The position of every third station in the traverse was determined from magnetic compass bearings on to local peaks included in the trigonometrical survey. The position of intermediate stations was determined by pacing and magnetic compass bearing. The locations of the gravity stations, given in Table 1, should not be in error by more than 0·5′ of latitude or 2′ of longitude. The differences in latitude between adjacent stations are correct to 0·1′, and in longitude to about 0·3′.

TABLE 1

In column 1, stations marked † are on glaciers and stations marked * are on the surface ice of Lake Vanda. Measured values of gravity are given in column 5. The Bouguer corrections, in column 6, assume that the rock between the point of observation and sea-level has a density of 2·67 g/cm^3. They include the free-air correction but not the terrain correction. Values marked † take account of the thicknesses of ice (of density 0·9 g/cm^3) shown in Fig. 2. Values marked * at stations on Lake Vanda assume that all the water is replaced by material of density 2·67 g/cm^3. In column 8 are given values of station gravity with the Bouguer and terrain corrections of columns 6 and 7 applied. In column 9 are given values for γo for the latitude of the station, given by the International Gravity Formula, 1931. The units of the quantities in columns 5, 6, 7, 8, 9, and 10 are cm/sec.^{2}.

1 Station No.	2 Alt. (m)	3 Lat. S	4 Long. E	5 Observed Gravity	6 Bouguer corr.	7 Terrain corr.	8 g corr.	9 γ°	10 Bouguer anomaly
Marble Point	68·9	77° 25·0′	163° 42·0′	982·9512	·0136	0	982·965	982·975	—·010
1	2	27·5′	43·6′	·9632	·0004	0	·964	·976	—·012
2	38	27·5′	42·2′	·9558	·0075	0	·963	·976	—·013
3	75	27·4′	41·0′	·9467	·0148	0	·961	·976	—·015
4	104	27·3′	39·8′	·9416	·0205	·002	·964	·976	—·012
5†	229	27·3′	38·5′	·9046	·052†	·002	·959	·976	—·017
6†	280	27·3′	37·4′	·8884	·066†	·001	·955	·976	—·021
7†	320	27·2′	36·3′	·8763	·077†	0	·953	·976	—·023
8†	344	27·2′	35·1′	·8680	·081†	0	·949	·976	—·027
9†	369	27·2′	33·2′	·8572	·087†	0	·944	·976	—·032
10†	399	27·1′	31·3′	·8550	·094†	0	·949	·976	—·027
11†	405	27·1′	29·4′	·8397	·095†	0	·935	·976	—·041
12†	408	27·0′	27·6′	·8376	·093†	0	·931	·976	—·045
13†	393	26·7′	25·6′	·8354	·090†	0	·925	·976	—·051
14†	387	26·5′	23·7′	·8340	·087†	0	·921	·976	—·055
15†	378	26·3′	21·7′	·8342	·084†	0	·918	·976	—·058
16†	378	26·0′	19·8′	·8295	·082†	0	·912	·975	—·063
17†	383	25·8′	18·1′	·8269	·083†	0	·910	·975	—·065
18†	378	25·5′	16·4′	·8290	·081†	0	·910	·975	—·065
19†	384	25·2′	14·7′	·8272	·083†	0	·910	·975	—·065
20†	378	25·1′	12·5′	·8260	·081†	0	·907	·975	—·068
21†	402	24·9′	10·3′	·8214	·088†	0	·909	·975	—·066
22†	427	24·7′	08·1′	·8146	·095†	·002	·912	·975	—·063
23†	427	24·9′	05·0′	·8052	·093†	·002	·900	·975	—·075
24†	463	25·2′	163° 02·3′	·7929	·102†	·004	·899	·975	—·076
25†	482	25·5′	162° 58·3′	·7816	·117†	·004	·903	·975	—·072
26†	480	25·6′	54·7′	·7796	·116†	·066	·902	·975	—·073
27†	472	25·6′	51·1′	·7821	·110†	·008	·900	·975	—·075
28†	450	25·7′	47·5′	·7880	·101†	·010	·899	·975	—·076
29†	389	25·9′	45·1′	·8055	·081†	·012	·899	·975	—·076
30	320	26·2′	43·1′	·8217	·0630	·014	·899	·975	—·076
31	302	26·4′	39·9′	·8230	·0595	·015	·898	·976	—·078
32	296	26·8′	36·4′	·8221	·0583	·017	·897	·976	—·079
33	290	27·0′	35·0′	·8207	·0571	·018	·897	·976	—·079
34	273	27·2	33·6′	·8206	·0538	·019	·893	·976	—·083
35	271	27·5′	30·9′	·8194	·0533	·020	·893	·976	—·083
36	268	27·8′	28·4′	·8165	·0528	·020	·889	·977	—·088
37	264	28·2′	25·9′	·8167	·0520	·022	·891	·977	—·086
38	251	28·5′	23·4′	·8170	·0494	·022	·888	·977	—·089
39	245	28·8′	20·9′	·8171	·0482	·024	·889	·977	—·088
40	256	29·2′	21·6′	·8164	·0505	·023	·883	·977	—·091

1 Station No.	2 Alt. (m)	3 Lat. S	4 Long. E	5 Observed Gravity	6 Bouguer corr.	7 Terrain corr.	8 g corr.	9 γ°	10 Bouguer anomaly
41	245	29·4′	20·0′	·8192	·0482	·023	·890	·978	—·088
42	242	29·6′	18·2′	·8194	·0476	·023	·890	·978	—·088
43	241	29·8′	16·4′	·8182	·0475	·023	·889	·978	—·089
44	236	30·1′	14·6′	·8180	·0465	·023	·888	·978	—·090
45	230	30·3′	12·5′	·8186	·0453	·024	·888	·978	—·090
46	230	30·6′	10·4′	·8184	·0453	·024	·888	·978	—·090
47	230	30·8′	08·5′	·8192	·0453	·024	·889	·979	—·090
48	227	30·9′	07·2′	·8183	·0447	·024	·887	·979	—·092
49	222	31·2′	05·0′	·8173	·0437	·024	·885	·979	—·094
50	207	31·3′	02·8′	·8179	·0408	·023	·881	·979	—·098
51	203	31·5′	162° 00·5′	·8183	·0400	·022	·880	·979	—·099
52	204	31·5′	161° 56·8′	·8176	·0402	·021	·878	·979	—·101
53	203	31·6′	53·2′	·8169	·0400	·020	·877	·979	—·102
54	198	31·7′	50·0′	·8176	·0390	·021	·878	·979	—·101
55	197	31·8′	47·1′	·8169	·0388	·024	·878	·979	—·101
56	192	31·9′	44·8′	·8172	·0378	·026	·881	·979	—·098
57	174	31·9′	42·5′	·8204	·0342	·029	·882	·979	—·097
Main Base	162	32·0′	40·2′	·8209	·0320	·032	·885	·979	—·094
58	143	32·0′	38·3′	·8238	·0282	·032	·884	·979	—·095
59	143	31·9′	35·5′	·8215	·0282	·032	·881	·979	—·098
60*	143	32·1′	32·5′	·8185	·0282*	·032	·878	·979	—·101
61*	143	32·3′	29·5′	·8136	·0282*	·032	·874	·979	—·105
62*	143	32·4′	26·4′	·8145	·0282*	·032	·875	·979	—·104
63	143	32·6′	23·4′	·8172	·0282	·032	·877	·980	—·103
64	183	32·7′	20·1′	·8065	·0360	·034	·876	·980	—·104
65	207	32·7′	18·7′	·7981	·0408	·036	·875	·980	—·105
66	165	32·8′	16·2′	·7998	·0325	·038	·870	·980	—·110
67	219	32·8	14·8′	·7918	·0431	·040	·875	·980	—·105
68	256	32·7′	12·8′	·7858	·0504	·040	·876	·980	—·104
69	232	32·6′	11·4′	·7883	·0457	·040	·874	·980	—·106
70	183	32·8′	09·7′	·7934	·0360	·040	·869	·980	—·111
71	207	32·9′	08·0′	·7872	·0408	·038	·866	·980	—·114
72	259	32·9′	06·2′	·7824	·0510	·040	·871	·980	—·109
73	347	33·1′	04·4′	·7688	·0683	·045	·871	·980	—·109
74	479	33·3′	02·4′	·7492	·0943	·045	·888	·980	—·092
75	610	33·5′	161° 00·4′	·7326	·1201	·045	·898	·980	—·082
76	750	33·8′	160° 58·1′	·7105	·1477	·040	·898	·980	—·082

The altitudes of gravity stations were determined by Paulin aneroid barometer. Indicated altitudes have been corrected for variations with time of the atmospheric pressure, these variations being obtained from continuous barograph recordings made at Main Base and at the U.S. Navy Air Facility, Marble Point. The stated altitudes are probably correct to ± 10 m.

In calculating the Bouguer corrections for the gravity stations in the valley, it has been assumed that all the material between the point of observation and sea-level has a density of 2·67 g/cm³. No allowance has been made for the deposits of unconsolidated moraine in the valley floor, the mean density of which is about 2·0 g/cm³. In the 20 km east of the western end of Lake Vanda the thickness of this moraine does not exceed a few metres, but further east and west it may be as much as 70 m, which would produce an error in the Bouguer anomaly of about 2 mgal. The procedures adopted for the parts of the traverse on the ice of Lake Vanda and on the glaciers are given below.

Until an accurate contoured map of the area has been produced terrain corrections can be only approximate. When possible, the traverse was made along the middle of the flat-bottomed valley, to minimise the errors. In calculating the terrain corrections two-dimensional models of the valley have been used. (King Hubbert, 1946). The floor of the valley is assumed to be flat, the actual sides are replaced by uniformly sloping sides of the same mean gradient and the mountain ranges north and south of the

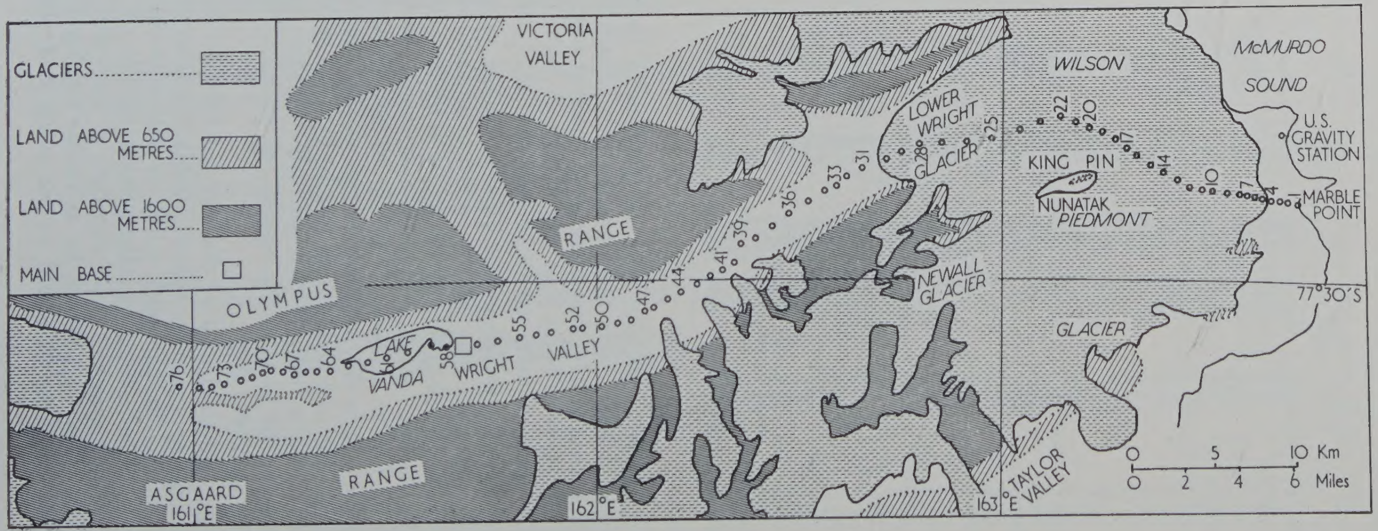

FIG. 2—Map of Wright Valley area showing location of gravity stations. Contours are approximate.

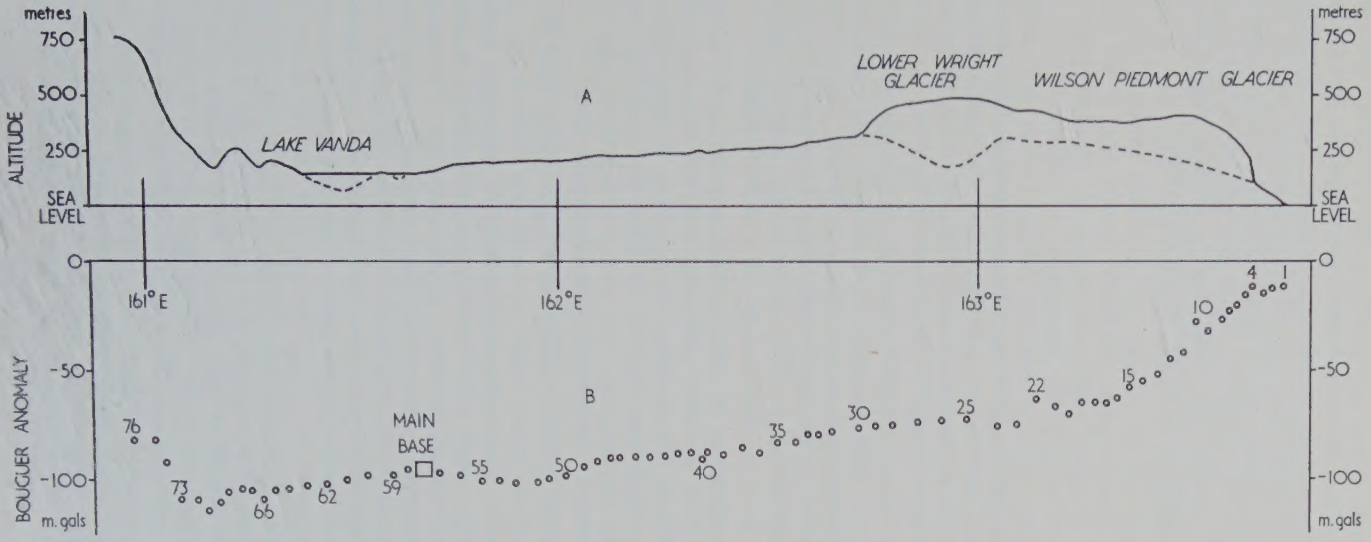

FIG. 3A—Longitudinal profile of Wright Valley and Wilson Piedmont Glacier along route of gravity traverse. Vertical exaggeration about 14 times.

FIG. 3B—Bouguer anomalies at gravity stations.

valley are assumed to extend indefinitely to the north and south, at constant altitudes. The density of the rock is again assumed to be 2·67 g/cm^3. For the stations on the coast and on the glaciers (stations 1–30) the terrain correction is less than 15 mgal, and the calculations should not be in error by more than 5 mgal. Along the Wright Valley the terrain corrections are greater, with values increasing to about 50 mgal at Stations 73–76. The errors should not exceed one third, and in general should be less than one-fifth, of the stated value of the terrain corrections.

RESULTS

The terrain-corrected Bouguer anomaly decreases steadily westwards along the Wright Valley from about — 75 mgal near the Lower Wright Glacier to about — 110 mgal at stations 70 and 71. Further west it increases again to about — 80 mgal at the end of the traverse. (Fig. 3B).

The uncertainty in the terrain corrections is greatest at stations 72–76, but the uncertainty is much less than the increase in the anomaly westwards in this section. Whether the increase continues further westwards cannot be decided until gravity measurements have been made on the nunataks west of the main mountain ranges. Such an increase would be expected if the whole mountain chain of Victoria Land is a horst formation.

Most of the decrease of the Bouguer anomaly along the valley between stations 31 and 70 is probably associated with the increased elevation of the country in the west. The gradient, 0·9 mgal/km, is comparable with those found in traverses from the lowlands of Italy or Austria into the eastern Alps, and in other similar areas, and is due to the thickening of the crust associated with isostatic compensation of the upland area.

Part of the gravity gradient along the Wright Valley may be associated with the tilting of the crustal block of which the valley is part (the tilt is about 5° downwards towards the west; Mr B. C. McKelvey and Mr P. N. Webb, pers. comm.), and with departure from isostatic equilibrium following the recent westward recession of the inland ice. The present eastern limit of the ice plateau is about 12 km west of gravity station 76. Formerly it extended eastwards at least as far as station 50. However it will not be possible to distinguish between these possible causes until further gravity traverses have been made in this and in adjacent areas where the block tilting is different.

The approximate depth of Lake Vanda at stations 60, 61 and 62 has been determined as follows. Firstly, it is assumed that the Bouguer anomalies which would have existed at these stations, if all the water were replaced by material of density 2·67 g/cm^3, follow the general variation along the valley found at neighbouring stations on land. The observed values of gravity at the lake stations are less than those required to give these interpolated Bouguer anomalies. The deficiencies are attributed to the replacement of material of density 2·67 g/cm^3 by water of density 1·0 g/cm^3. No allowance has been made for the variation of the depth of water at points surrounding the gravity station. The deficiencies at stations 60, 61, and 62 are 3, 5, and 2 mgal respectively, corresponding to depths of water of 43, 72, and 29 m.

Unfortunately the same method cannot be applied to determine the thickness of ice in the Lower Wright and Wilson Piedmont Glaciers because the gravity gradient of 0·9 mgal/km, which exists in the valley, does not continue steadily to the coast. The Bouguer anomaly increases from about — 75 mgal at the inland edge of the Lower Wright Glacier to about — 10 mgal on the coast near Marble Point. It is impossible to determine accurately the Bouguer anomalies at stations on the glaciers because the thickness of ice is not known. However, approximate values for the ice thicknesses and Bouguer anomalies have been obtained by the following procedure. It is reasonable to assume that the Bouguer anomalies at stations 29–25 follow the same regional gradient as exists further west in the Wright Valley, because there is no abrupt change in the form of the mountain ranges north and south of the Wright Valley west of longitude 163° E and because no geological faults have been observed in these ranges between the longitude of the end of the Lower Wright Valley and their eastern limit, 163° E. The thickness of ice at stations 29–25 is calculated simply from the gravity deficiencies, in the manner described above. East of station 25 the character of the Wilson Piedmont Glacier is that of a small ice-sheet rather than a valley glacier so that the ice thickness at points away from the edge can be calculated approximately from a knowledge of the slope of the top surface. (Nye, 1952.)

The form of the bottom surface of the ice, given by these methods, is shown in Fig. 2A, and the corresponding values of the Bouguer anomalies in Fig 2B. Although errors of up to 5 mgal may exist in the Bouguer anomalies calculated for individual stations, the general pattern is clear. Over the 10 km from station 16 to the coast the gradient of the anomaly is 5 mgal/km[1]. Whether the eastward increase of the anomaly stops near the coast or continues into McMurdo Sound is uncertain from the present results.

It has been suggested (David and Priestley, 1914) that a major north-south geological fault occurs along the western coast of McMurdo Sound, the mountains of Victoria Land being on the upthrown side. The conclusion drawn from the present measurements of gravity is that such a fault could exist either along the coast or a few kilometres inland. However, the Bouguer anomalies are lower to the west, so that if the upthrust side is west of the fault much of the material raised above sea-level during the upthrust must be of greater density than the average for the crustal section. Since the two thick dolerite sheets which intrude the basement rocks of the Wright Valley area could by themselves account for about 15 mgal of the change in the anomaly, this interpretation may not be unreasonable.. A complete explanation must take into account that the areas of present and recent volcanic activity are all east of this fault line.

Obviously there is here a problem of some importance. Unfortunately the existing data is not sufficient for a full solution but it is hoped that the gravity results gathered in the next few years will permit a worth-while interpretation to be made.

ACKNOWLEDGMENTS

It is a pleasure to thank again those whose help made the Expedition possible: the Research Grants Committee of the University of New Zealand and the Council of the Victoria University of Wellington for funds; many commercial firms in New Zealand for generous gifts of materials; the Ross Dependency Research Committee for their advice and help in many ways; and the executives and members of U.S. Operation Deepfreeze IV for transport and general cooperation while we were in the field.

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SHALLOW TEMPERATURE SURVEYING IN THE WAIRAKEI-TAUPO AREA

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Summary

The 1-metre temperature probe has proved of value in indicating the boundaries of subsurface heat storage at Wairakei. It provides a method of rapid reconnaissance, indicating areas worthy of further investigation by drilling. Examples are given of its use as a prospecting tool on the Wairakei power projects and on a small survey for domestic requirements.

INTRODUCTION

In the early days of geothermal exploration in New Zealand the total natural heat discharge from an area was obtained by the summation of the heat lost from regions of directly visible thermal activity, *viz.*, geysers, hot springs, fumaroles, etc., and although some attempt was made to include the heat lost from extensive areas of steaming ground by counting the number of active vents per unit area, the assessment could only be a conservative one, with much lesser activity still being ignored. Methods were later developed to measure more accurately the discharge from steaming ground (Benseman, 1959 a, b), but some system of rapidly defining the outer limits of the hot ground was still required, and various methods of shallow temperature measurements were therefore investigated.

EXPERIMENTAL METHOD

Trial temperature probes and gradiometers were constructed and tested in the field, and from experience with these, the design now in use was evolved. The probe consists of a length of wooden dowelling with a single copper-constantan thermocouple mounted at the tip (Fig. 1). It is inserted in a hole punched into the ground to a depth of 1 metre by a $\frac{5}{8}$ in. diameter high tensile steel rod, driven by a hand operated weight moving between two collars at the top of the rod. A depth of 1 metre was chosen as a compromise between two factors, the speed of operation and the magnitude of seasonal and diurnal temperature variations. After a stabilisation period of from one to four minutes, depending on the temperature at each location, the thermo-emf is read to the nearest 10 microvolts (0·25°C) on a portable potentiometer. Because of the necessity of eliminating any stray emf's from the measurement, the reference junction, kept in a thermos filled with melting ice, was electrically insulated.

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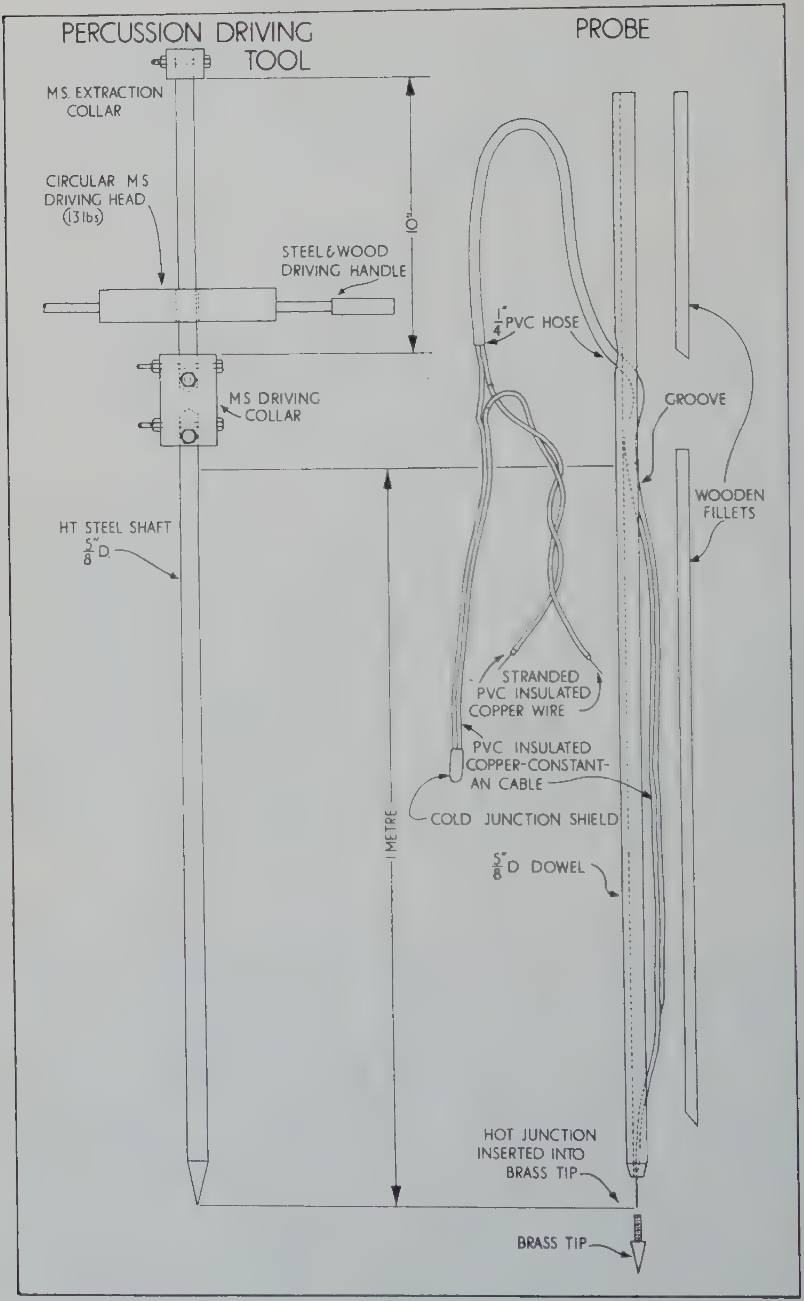

FIG. 1—Design of temperature probe and driving tool.

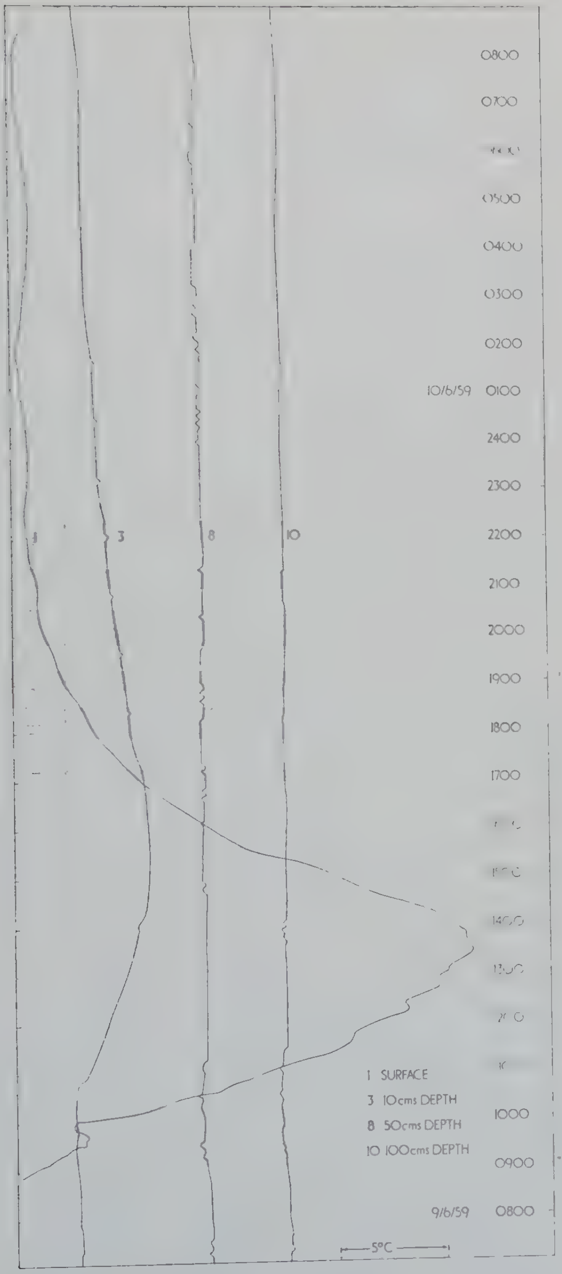

FIG. 2—Diurnal variation of ground temperature.

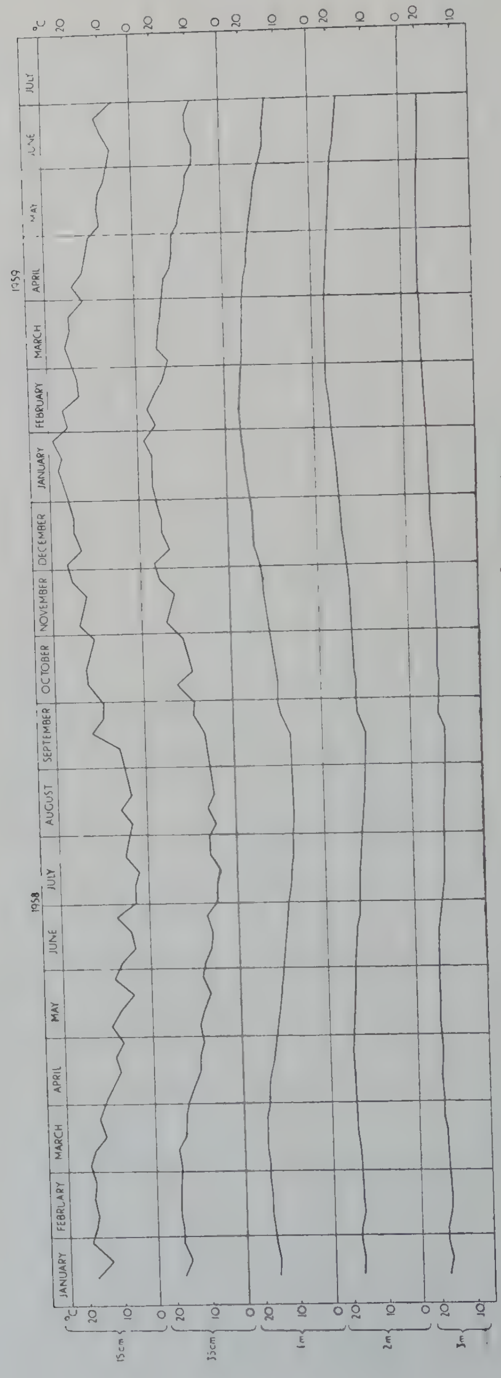

FIG. 3—Seasonal variation of ground temperatures.

The field party consists of three members, and at least two probes are in the ground at any one time. While one member of the party is taking the potentiometer reading on the first probe, the second probe is already inserted at the next measuring point to allow temperatures to stabilise, and the remainder of the party are locating and installing the third probe still further ahead. In this way a fairly rapid coverage of an area is possible, a daily average of 40 to 50 stations at 200-ft spacing being maintained without much difficulty.

It is well known that diurnal and seasonal changes have an effect on ground temperatures; indeed one of the chief objections to shallow temperature surveys is that these variations could well obscure the required temperature pattern. However, regular measurements of temperature in a permanent installation at Wairakei have shown that at 1 metre, no diurnal effect is apparent (Fig. 2), and that seasonal changes follow a well defined sine curve, whose amplitude decreases with depth (Fig. 3). Because Wairakei is mantled by very uniform volcanic ash, or alluvium derived from it, we may assume that the thermal diffusivity of the ground does not vary greatly over the area of the survey. It is therefore possible to use curves such as those of Fig. 3 to adjust, to a common base value, field surveys made at different seasons. Reference stations are established in various parts of the field for this purpose, with a single thermocouple at the bottom of a 1-metre hole, backfilled with sand or fine soil, and in addition a permanent reference station has been installed close to the laboratory, at which the curves shown in Figs. 2 and 3 were recorded.

Two examples of the use of the method are described.

(1) The first is that of an extensive survey which requires careful "base" control to allow for the effects of seasonal variations in temperature occurring during the survey. Here the object is to indicate the extent of heat storage and thus outline the area which merits further investigation with a view to steam production and power generation.

(2) In contrast, the second example is that of a limited survey where greater detail is required and only one day's field work is necessary.

(1) *Temperature Probe Survey at Wairakei*

Between June 1957 and June 1959, this survey at Wairakei has covered an area of about 15 square miles, shown in Fig. 4, with boundaries roughly defined by the Old Taupo Road, the main Taupo-Rotorua highway, and by the Wairakei-Tirau highway.

Fig. 4 shows the temperature survey lines and the isotherm map compiled from them. In the initial experimental stages, a rather detailed survey was made around the present steam production area, the station spacing being generally fairly close (30–40 ft). But it was subsequently decided that the hottest areas are better measured by shorter temperature probes, and work with the metre probe was restricted to the boundaries of the hot areas; the spacing was then expanded to 200 ft, except in places of rapid temperature change where a spacing of 100 ft or 50 ft was reverted to. Where the survey lines have not cut completely across known areas of surface thermal activity, but where it was already known that ground temperatures were high, isotherms are shown dotted. All temperatures are plotted relative to the permanent thermocouple base outside the laboratory at Wairakei as at August 1958.

It is interesting to analyse the temperature data obtained from some of the Wairakei steam bores in the light of the 1-metre temperature results. At first sight it would seem unlikely that near surface temperature measurements could reliably indicate conditions at depth, but having regard to the homogeneous and permeable nature of the upper strata at Wairakei, the agreement found is not surprising. Some inconsistencies do occur, but these in no way detract from the value of the method in rapidly surveying the limits of subsurface heat storage on a broad scale. Two sections have been taken through drilled holes, and isotherms have been plotted using results obtained from temperature runs made by the Ministry of Works.

One of these sections (Fig. 5) passing through bores 203, 211, and 34 shows falling isotherms from West to East across the profile. At the top of the section can be seen plotted detail of the 1-metre temperatures and the agreement with bore isotherms is quite evident.

The second section (Fig. 6) from bore 13 to bore 58 cuts across the extensive cold block in which bore 34 is located. Here again there is agreement with temperatures at 1-metre depth, but it is worthy of note that although the temperatures in bore 34 (also bore 35) are considerably lower than those in either bore 13 or bore 58, there is nevertheless a positive temperature gradient in the hole. However, the highest temperature (199°C) is not reached until the bottom of the hole at 1,996 ft (684 ft below datum), and the gradient is linear throughout, indicating conductive heat flow. It is therefore apparent that although the method is capable of defining the boundaries of hot areas, it cannot be expected to give an infallible indication of the prospects of good steam production from depths of a thousand feet or more.

(2) *Temperature Probe Survey at Taupo*

The method has been successfully applied in limited areas where local bodies have desired information on the possibility of obtaining a supply of hot water for baths, central heating of buildings and for other purposes. The second example to be quoted, deals with a survey designed to obtain information on subsurface conditions at the site of a proposed new primary school at Taupo.

It was already known that some areas of thermally altered ground were located nearby, but further information was sought in order that excavations for foundations could proceed without the embarrassment of high temperatures. It was also hoped that some indication of the possibility of locating a source of hot water for heating the school would result from this survey, and in both of these objectives the method has proved most useful.

In contrast to the previous example, only one day's field work was involved in the survey, so that there was no need to adjust the temperatures measured to account for short term seasonal changes as before. The results plotted in

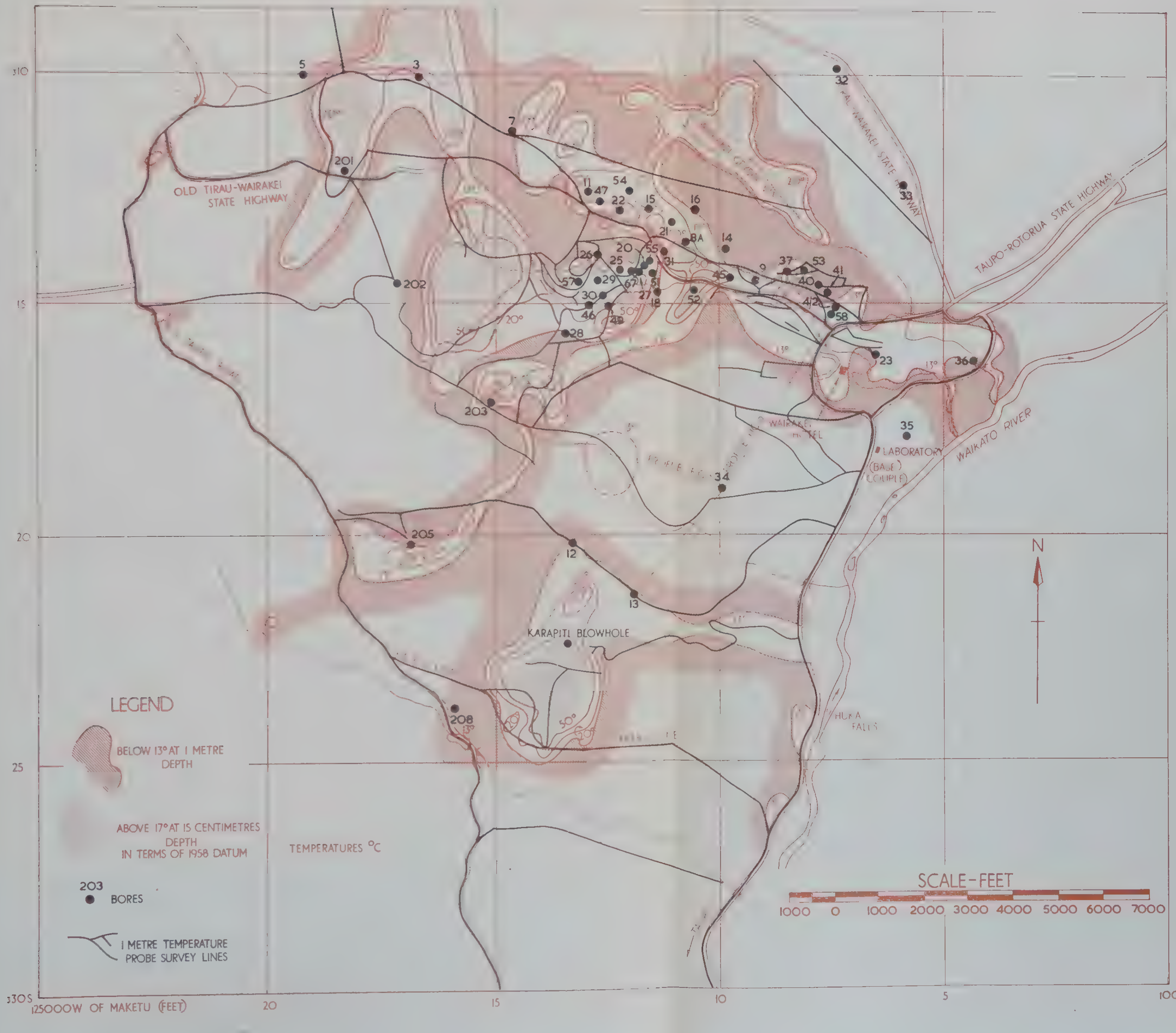

FIG. 4—Shallow-temperature survey of Wairakei hydro thermal field.

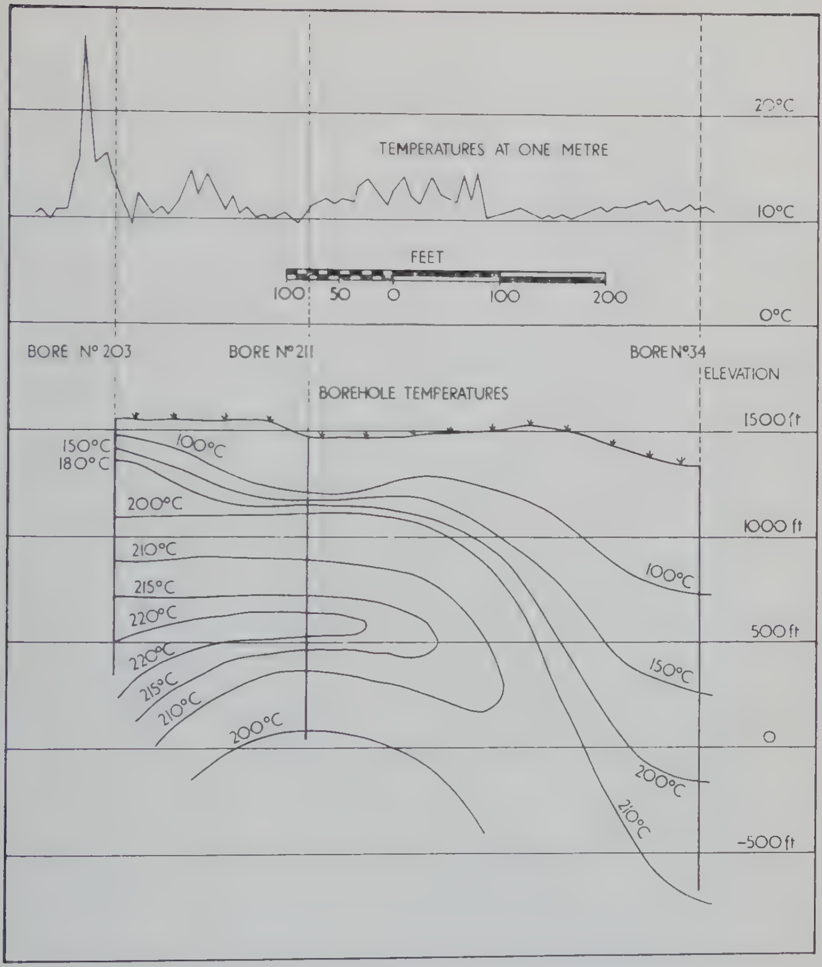

FIG. 5—Comparison of shallow and deep temperature measurements.

Fig. 7 show quite clearly the existence of two well defined hot zones at a depth of 1 metre, and while the temperatures measured were not expected to affect the location of the buildings proposed, there was every indication that a satisfactory solution to the heating problem would be found at either of these two zones. In a subsequent test drilling on the temperature high adjacent to Classroom Block A, boiling water was found at a depth of 150 ft.

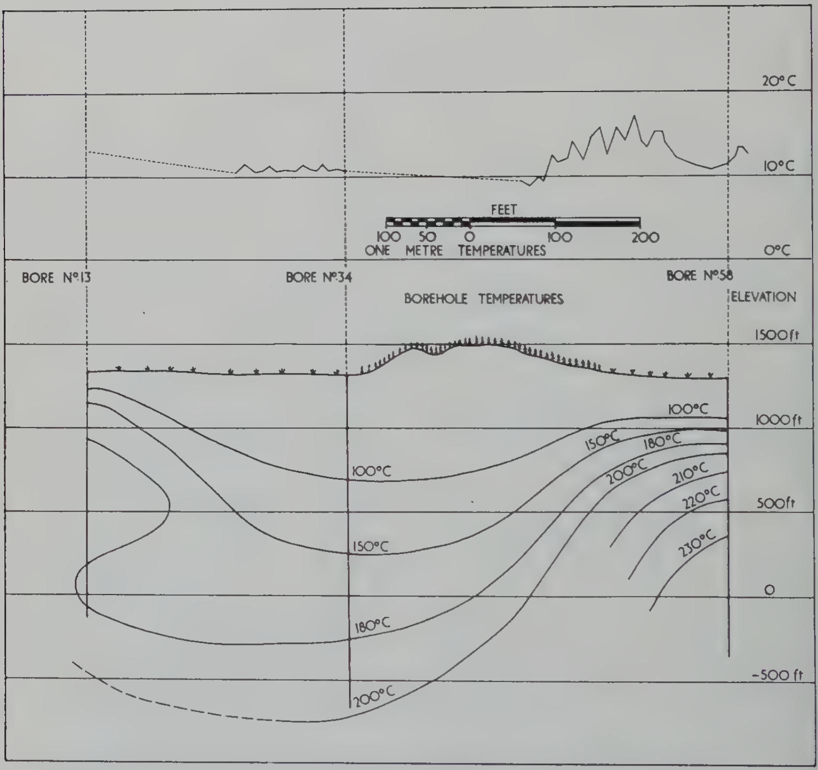

FIG. 6—Comparison of shallow and deep temperature measurements.

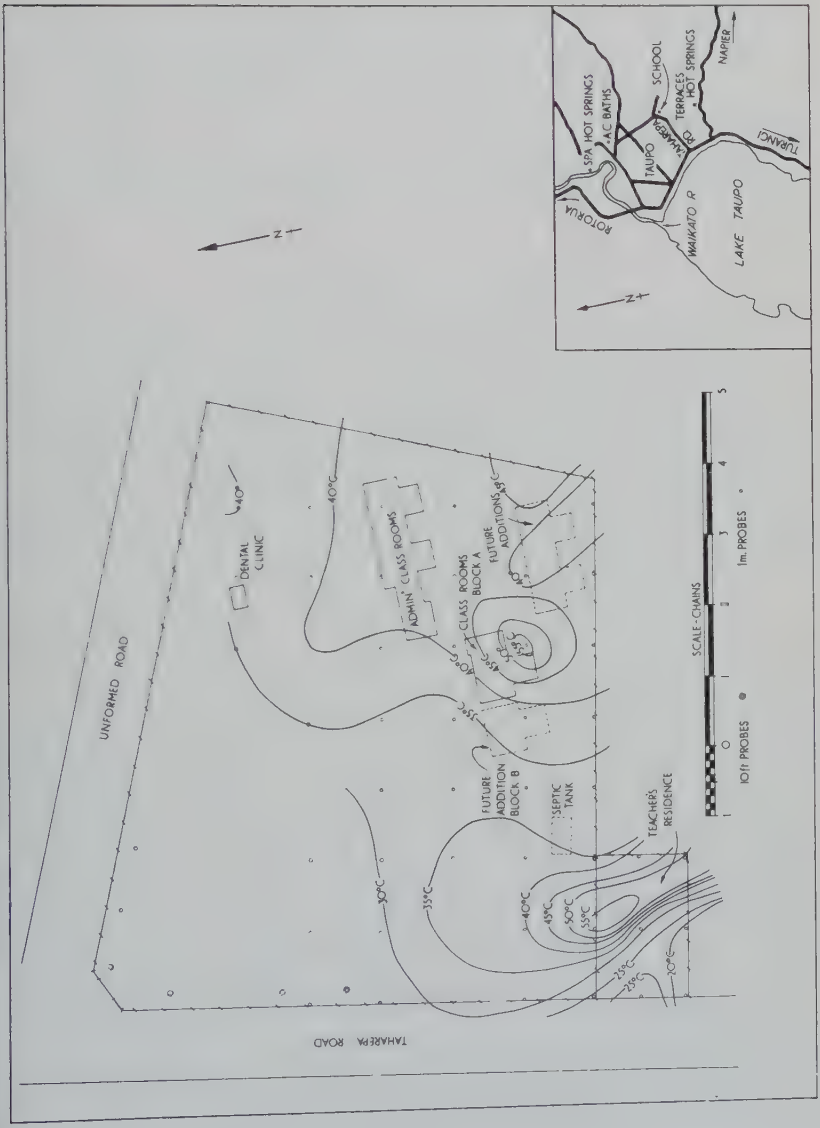

FIG. 7—Temperature survey of school site.

CONCLUSION

At Wairakei, the 1-metre temperature probe has proved itself capable of defining areas of stored heat from which useful supplies of energy can be withdrawn. It has shown the existence of a promising area northwest of the Wairakei Hotel where no holes have as yet been drilled. In general, the 1-metre temperature contours correlate well with isotherms obtained from temperature runs in drilled bores.

The method has also proved of value in rapidly surveying localised areas of heat discharge and in determining the most advantageous location for test drilling.

ACKNOWLEDGMENTS

Thanks are due to: the Project Engineer, Ministry of Works, Wairakei, for permission to use the temperature data obtained from drilled bores; to the staff of the Geothermal Laboratory at Wairakei for their effort in the field, and to the design section of the Dominion Physical Laboratory for assistance in designing the tool used for driving the 1-metre holes.

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THE ECOLOGICAL SIGNIFICANCE OF SOME EARLY SEA TEMPERATURE RECORDS FROM OTAGO HARBOUR

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(Received for publication, 9 February 1960)

Summary

Recorded sea temperatures for Portobello, Otago Harbour, for 1905 and 1906 are approximately 3°C lower than recent temperatures from the same recording station. Comparison of available temperature records for this locality with Dunedin temperatures over the same period suggests that the anomaly is due to an instrumental calibration error rather than a significantly lower temperature regime for those years. Thus, the local fauna does not necessarily tolerate sea temperatures as low as those previously published, and deductions of earlier workers on the effects of low temperatures on fish-rearing experiments at Portobello may be invalidated.

INTRODUCTION

There are very few records of daily sea temperatures for New Zealand ports over any length of time prior to 1950 available in the literature. For Otago Harbour (Fig. 1) there are only those from Portobello for 1905–06 recorded by Thomson (1905) and Anderton (1906), and some monthly maxima and minima given by Brewin (1952). These records are of importance in assessing temperature ranges in Otago Harbour and their significance in local and regional faunal studies. Thomson and Anderton have laid some stress on the significance of temperature in fish-rearing experiments and their figures have already been incorporated in at least one ecological paper (Oliver, 1923). Although contemporary records are now available from Portobello Marine Biological Station, the Thomson and Anderton records still merit attention as they give much lower minimum temperatures than any since recorded.

The attention of one of the authors (D.E.H.) was drawn to these early records while working on biological data from Portobello (Hurley, 1959). It was noted that, not only were the minimum sea temperatures quoted much below recent ones, but that the summer temperatures were also unusually low. It seemed possible that a constant error in thermometer calibration might be involved and because of the importance of such low minimum temperatures (1°C) on animal life-histories, information was sought for or against this possibility. There is evidence that a hitherto unsuspected error in calibration was responsible for these low readings.

N.Z. J. Geol. Geophys. 3 : 563–71

Comparison of Temperatures

The lowest reported daily sea temperatures recorded at Portobello are 1·6°c on 5 June 1905 (Thomson, 1905); 1°c on 17 July 1906 (Anderton, 1906); 3·3°c in July 1945 (Brewin, 1952); and 4·8°c on 13 July 1952, and 28 July 1954 (Batham, 1956). All except Brewin's are 9 a.m. temperatures. Thomson's and Anderton's records are thus noticeably lower than any others.

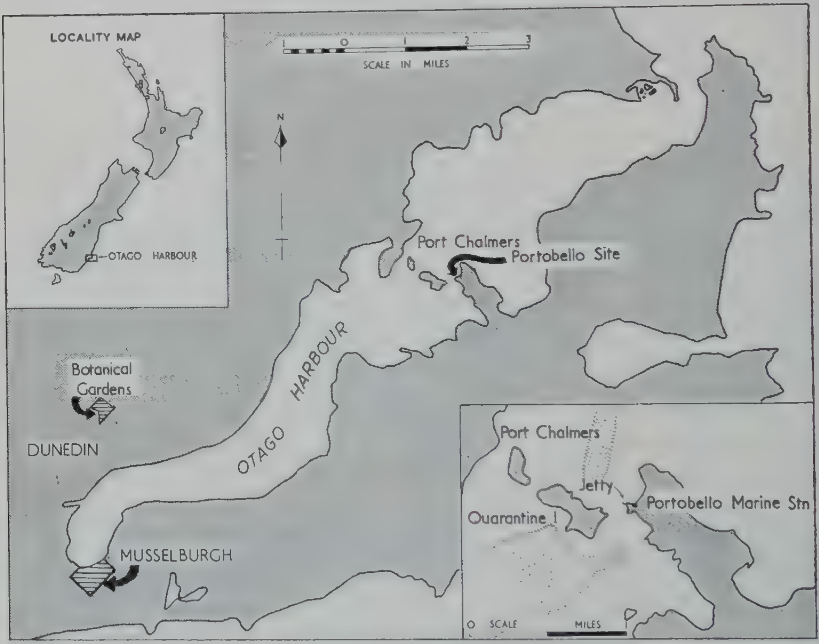

Fig. 1—Locality map showing Dunedin Botanical Gardens, Musselburgh, and Portobello temperature recording sites.

Monthly averages of sea temperatures at Portobello during 1905 (Thomson, 1905), 1906 (Anderton, 1906) and for the period July 1952 to March 1954 Batham, 1956 and records held at Portobello Marine Biological Station) are given in Table 1. The monthly means during 1905–06 are 1·9°c–5·7°c lower than those during the corresponding months of 1952–54. Thomson and Anderton do not give December values for 1905 or 1906, but the 11-monthly means shown in the table also reflect these differences.

Monthly means of air temperatures at Portobello for the same months of 1905 and 1906 (Thomson, 1905; Anderton, 1906) and 1952–54 (Batham, 1956) are shown in Table 2. As with the sea temperatures, the monthly means for 1905–06 are 1·1°c–5·2°c below the corresponding monthly means for 1952–54 and the 11-monthly means display similar differences.

TABLE 1—Monthly Averages – Sea Surface Temperatures at Portobello (in °C)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	11-Month Average
1905	10.8	12.9	11.4	8.2	6.1	3.1	2.9	3.7	5.5	7.4	10.0	......	7.42
1906	11.6	10.2	9.5	6.6	4.8	3.3	2.7	3.4	5.8	7.6	9.3	......	6.79
1952	......	......	......	......	......	......	5.8	7.6	9.7	11.8	12.8	(15.9)	
1953	16.1	15.0	13.3	10.6	8.9	7.1	6.1	7.3	9.1	11.0	13.4	(14.7)	10.6
1954	15.6	15.9	14.8	......	......	......	......	......	......	......			

TABLE 2—Monthly Average Air Temperatures at Portobello, 1905–06 and 1952–55 (in °C)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	11-Month Average
1905	10.6	12.4	11.2	7.8	5.4	2.8	3.0	3.4	5.1	6.9	10.2	......	7.12
1906	11.9	9.9	9.0	7.1	3.7	3.8	2.6	3.4	6.4	7.3	10.1	......	6.83
1952	......	......	......	......	......	......	5.1	6.7	9.2	11.1	11.3	14.9	......
1953	14.3	13.9	13.0	10.6	8.9	6.4	5.8	7.1	10.0	11.9	13.6	14.6	10.48

TABLE 3—Monthly Average Air Temperatures at Dunedin Recording Sites, 1905–06 (Dunedin) and 1952–53 (Musselburgh) in °C

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	11-Month Average
1905	12.0	14.2	13.7	9.7	7.4	5.4	5.5	6.3	7.0	8.8	11.2	12.8	9.11
1906	12.5	11.8	11.0	9.7	7.8	7.2	5.3	6.4	8.0	10.8	11.1	14.3	9.28
1952	13.8	15.2	13.2	11.8	9.2	6.0	5.9	7.7	9.6	11.1	11.2	15.1	10.43
1953	14.2	13.9	13.4	10.7	8.6	6.0	6.4	7.4	9.6	10.5	13.7	14.2	10.40

It is not clear, using published data alone, whether the 1905–06 anomalies described above were due to the use of one thermometer for both sea and air temperature observations in those years and a differently calibrated thermometer in 1952–54, or to a change in technique, or to a real difference of approximately 3°C between the two periods.

The differences between the sea and air temperatures in the 11-monthly means for 1905, 1906, and 1953 are respectively 0·30°C, — 0·04°C and 0·12°C. Since the measurement of a sea surface temperature should not introduce consistently anomalous values, these small differences indicate that consistent methods were followed; the anomalies are therefore unlikely to be due to changes in technique.

The possibility of a real difference in temperature levels between 1905–06 and 1953 has therefore to be considered. There is evidence that the winter of 1905 was particularly cold. On 4 July, snow lay 3–4 in. deep on the ground at Portobella (Thomson, 1905). Air temperatures in Auckland were slightly colder than average, and in Wellington the yearly air temperature means for 1905 and 1906 were 0·5°F and 1·4°F below normal (N.Z. Meteorological Office records.) However, the likelihood of a real difference can be shown to be highly improbable.

The *fluctuations* of the recorded annual mean temperatures at Portobello (Fig. 2) correspond closely with those observed at Dunedin* for the period 1906–1916, and again for the period 1917–27, but the *curve* for the Portobello temperatures indicates that there was an abrupt change in the recorded values between these two periods which was not reflected in the Dunedin temperatures.

The monthly means at Portobello (Table 2) and at Musselburgh* during the same month (Table 3) differed during 1952–53 by no more than 1·4°C, while the annual means for 1953 were 10·82°C and 10·72°C respectively. This close agreement does not hold for temperatures recorded at Portobello and Dunedin during 1905 and 1906 (Fig. 2). The mean of the annual means at Musselburgh for the period 1947–58 is 11·0°C and that at Dunedin between 1886 and 1940 was 10·5°C. This difference is much less than that between the annual means for 1906 at Portobello (7·5°C) and at Dunedin (9·7°C), and between the differences in the 11-monthly means, 6·83°C and 7·12°C at Portobello and 9·11°C and 9·28°C at Dunedin for 1905 and 1906 respectively.

By using the "Student's t-test" we may determine the probability that any two groups of recorded data have been derived from a consistent set of observations on a statistically steady phenomenon. The means, number of observations and standard errors of the data in Table 4 for the two periods 1906–16, 1917–27 at Portobello and Dunedin are given in Table 5, together with values of t for testing between pairs of groups and the

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*There have been changes in site and height above sea-level of the Dunedin recording site in this period. From 1864 to 1885 the site was in the Botanical Gardens at a height of 464 ft above sea-level; from 1886 to 1940 it was 350 ft above sea level; from 1941 to 1947 it was 690 ft above sea-level; and since 1947 it has been situated at Musselburgh, between Dunedin and Portobello (Fig. 1), 5 ft above sea-level. These heights are indicated in Fig. 2. The Portobello air temperature site is estimated (D.E.H.) to be about 10 ft above sea-level.

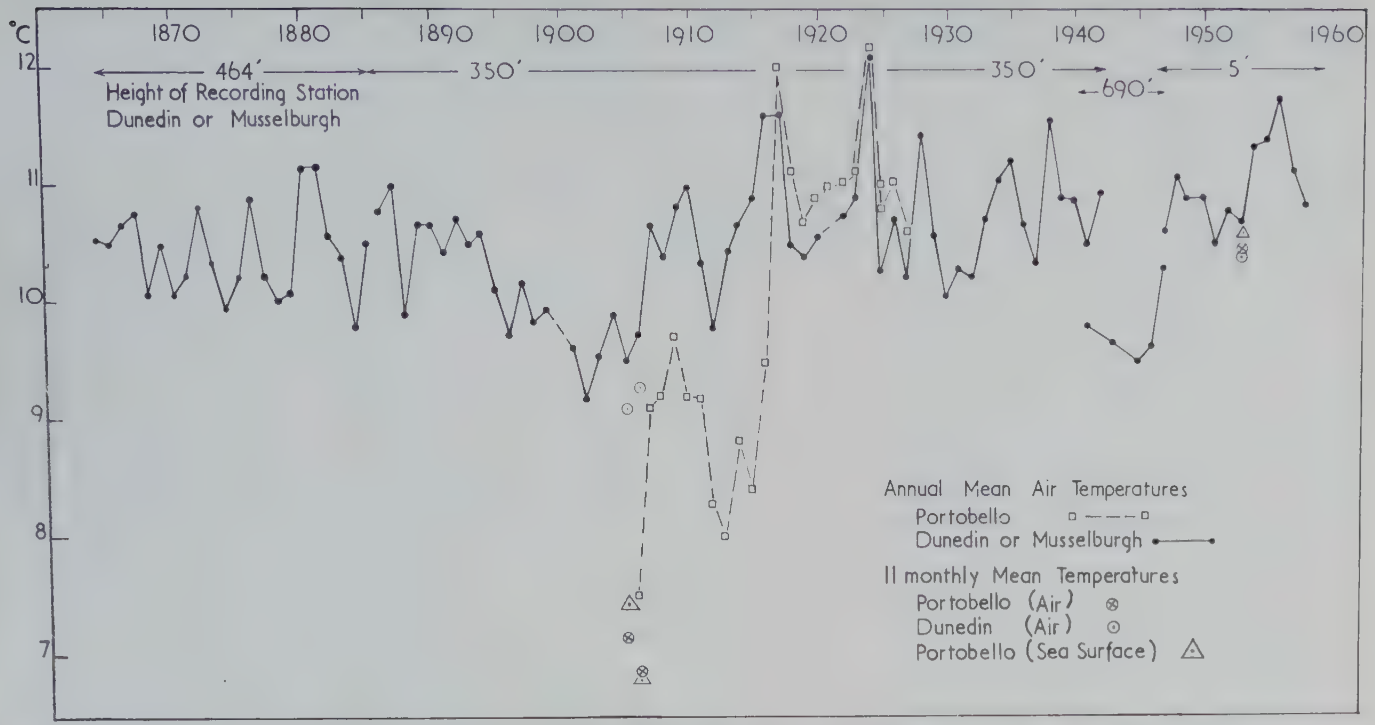

FIG. 2—Annual mean air temperatures at Dunedin and Musselburgh sites from 1864 to 1959 compared with Portobello temperatures from 1906 to 1927; also 11-monthly mean temperatures at Portobello (air and sea) and Dunedin (air). The Portobello annual mean air temperature for 1953 (not shown) was 10.82°c.

probability that for each pair the same phenomenon was consistently recorded. From the comparison between the two periods at Dunedin ($p = 0{\cdot}37$) it is seen that the small differences in the recorded means may arise through chance and that there is no significant change in mean temperature level between the periods. The test also shows that the recorded observations at Portobello and Dunedin during 1917–27 were essentially drawn from the same air temperature states and that the small difference in mean temperatures over the period at the two places may have arisen by chance ($p = 0{\cdot}20$). Thus, with consistent methods of observation it would be expected that the mean at Portobello for the 1905–06 period would not differ except by chance from that at Dunedin during the same period nor from that at Portobello during the later period.

However, the t-test shows that there is an extremely small probability (very much less than one in 1,000) that the temperatures observed at Portobello were derived from the same phenomenon by a consistent method. Since there is control exercised over the methods of observation and calibration of thermometers by the N.Z. Meteorological Service at their recording stations, the Dunedin temperatures must reflect the climatological situation.

TABLE 4—Mean Annual Air Temperatures at Portobello and Dunedin, 1906–27*

Portobello (Sea-level)			*Dunedin* (Altitude 350 ft)		
		(°c)			(°c)
1906	......	7·5	1906	......	9·7
1907	......	9·1	1907	......	10.7
1908	......	9·2	1908	......	10·4
1909	......	9·7	1909	......	10·8
1910	......	9·2	1910	......	11·0
1911	......	9·2	1911	......	10·3
1912	......	8·3	1912	......	9·8
1913	......	8·0	1913	......	10·4
1914	......	8·8	1914	......	10·7
1915	......	8·4	1915	......	10·9
1916	......	9·5	1916	......	11·6
1917	......	12·0	1917	......	11·6
1918	......	11·1	1918	......	10·5
1919	......	10·7	1919	......	10·4
1920	......	10·9	1920	......	10·6
1921	......	11·0	1921	......	......
1922	......	11·0	1922	......	10·7
1923	......	11·1	1923	......	10·9
1924	......	12·1	1924	......	12·1
1925	......	10·8	1925	......	10·3
1926	......	11·0	1926	......	10·7
1927	......	10·6	1927	......	10·2

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*Values obtained from data preserved at the New Zealand Meteorological Office.

We have already excluded the possibility of inconsistency of the method in the Portobello records because of the close agreement between air and sea surface temperatures during 1905–06 and during 1953. The remaining possibility, supported by the data above, is that the calibration of the thermometer used during the 1905–16 period is lower than that used during the later period by 2·3 ± 0·85°c. It is perhaps relevant to note that the Curator at Portobello, Mr Thomas Anderton, who is presumed to have been responsible for the temperature records, died quite suddenly in 1916 and subsequent changes in the establishment may have led to the replacement of the thermometer or thermometers in use.

TABLE 5—Application of t-Test to Temperatures at Dunedin and Portobello

Station	Period	Mean °c	Number of Observations	Standard Error °c		p*
(A) *Portobello*						
	1906–16	8.81	11	0.68	t = 9.15	very small
	1917–27	11.12	11	0.49		
(B) *Dunedin*						
	1906–16	10.57	11	0.54	t = 0.91	0.37
	1917–27	10.80	10	0.60		
(C) *Comparison of Dunedin and Portobello*						
	1906–16	......	......	......	t = 6.7	very small
	1917–27	......	......	......	t = 1.34	0.20

*Values from statistical tables for 19 degrees of freedom

p =	0.4	0.3	0.2	0.01	0.001
t =	0.86	1.07	1.33	2.86	3.88

In view of the anomalies described above, it is suggested that, although the relative temperature range shown by these early records may be valid for the years concerned, the absolute temperature values should be treated with reserve and minimum temperature ranges tolerated by animals in Otago Harbour should be based on recent temperature measurements only.

DISCUSSION

Portobello Marine Station, the site of these early Otago Harbour sea temperature records, was originally used as a fish-hatchery in an unsuccessful attempt to introduce European fish and lobsters to New Zealand waters. In their accounts of this work, Thomson and Anderton place considerable importance on the deleterious effects of low temperatures on their success.

Of the exceptionally cold period in June 1905, Thomson (1905) says: "On the 5th June, the temperature of the water in the ponds fell to 0°c, but the cold did not seem to trouble the fish [*Rhombosolea plebeia** Richardson and *Rhombosolea tapirina* Gunther]. On the 7th June, with the temperature of the water at 1·2°C, they were feeding quite freely . . . Heavy snow came on during the night, and on the morning of the 4th it lay 3 in. or 4 in. deep on the ground, while the temperature of the pond went down to 0·8°C. One of the cod [*Parapercis colias* Forster] was found dead and five or six more were lying on their sides in a nearly dead condition. During the night the temperature fell still lower, that of the pond standing at 0°C, and on the morning of the 5th the rest of the fish were lying on their sides, all dead but five."

Thomson and Anderton (1921) remark that "several lots of the larvae of local flat fishes have been killed owing to the temperature of the water in the boxes going as low as 1°C, and larvae that have been hatched at a temperature of 2°C have exhibited marked physical weaknesses". Again, "The eggs of the crayfish [*Palinurus edwardsii*] hatched during November and December . . . the whole process is performed in thirteen months in our waters; but it is highly probable that the extra month [over the time required by the European lobster, *Homarus vulgaris*] is accounted for by the low winter temperatures of our shallow ponds and the consequent retardation in the development of both the external and ovarian eggs. I have not been able to obtain particulars of the daily temperatures experienced around the English coast, . . . but . . . Mr H. C. Chadwick, curator of the Biological Station at Port Erin, Isle of Man . . . states that the lowest temperature is 40°F (=4·4°C) in February." They then quote minimum temperatures in the spawning pond at Portobello for June, July and August of 2·0°, 1·4° and 1·2°C respectively.

Anderton (1906) comments: "In the twenty-second Annual Report of the Scottish Fishery Board, the minimum temperature recorded during 1903 was 5°C, and this was recorded on one day. The usual midwinter temperature appears to be about 7°C and the maximum 13·2°C . . . From our brief experience here it would appear as if even a slight reduction is fatal to the incubation of the eggs. I think, from the slight difference in the temperatures of the British and local waters, we may conclude that any European fishes, once introduced, would not be injuriously affected by the slight change in ocean waters but that the only difficulty would be in keeping the adult fish in our ponds without some means of raising the temperature through the winter months, during which the temperature has at times fallen below 0°C."

Anderton gives mean hatching temperatures for a number of local fish: 5·5°C for five days for brill (*Caulopsetta scapha*), 9°C for 5 days for flounder (*Rhombosolea plebeius*), and 5°C for 5 days for sole (*Peltorhamphus novae-zealandiae*).

It is exceedingly difficult to determine what value to place on these findings. Those emphasising differences between sea and pond temperatures and the effects of low temperatures in ponds and hatching boxes on fish mortality may be valid; the absolute temperature values are probably 2–3°C too low.

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*No attempt has been made to bring Thomson's and Anderton's specific or generic names into line with current usage.

ACKNOWLEDGMENTS

Thanks are expressed to the Director and Scientific Officers of the New Zealand Meteorological Office for providing mean annual temperatures for Dunedin (1864–1958) and Portobello (1906–27) and for computing the mean annual values for Portobello data.

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AGE RELATIONS OF THE DUNEDIN VOLCANIC COMPLEX AND SOME PALEOGEOGRAPHIC IMPLICATIONS—PART II

By D. S. Coombs, A. J. R. White, and D. Hamilton, Geology Department, University of Otago, with an appendix "Plant Microfossils from the Middlemarch Diatomite" by R. A. Couper*, New Zealand Geological Survey, Lower Hutt.

(Received for publication, 19 February 1960)

Abstract

An attempt is made to determine the duration of the Dunedin volcanicity which was shown in Part I (Coombs, White & Hamilton, 1960) to have been initiated during Waiauan or early Tongaporutuan times.

Paleobotanical data offer potential indicators of age since carbonaceous beds are widely distributed at various horizons within the volcanic sequence but present microfloral evidence is indecisive. It indicates an age from Waiauan to Opoitian for material deposited during the intervals between both the First and Second, and Second and Third Major Eruptive Phases.

From the occurrence of Third Phase phonolite boulders in Late Pleistocene soliflual deposits, the deep weathering of some of these phonolites and the general lack of constructional landforms in the Dunedin district, it is suggested that volcanic activity was complete not later than early Pleistocene and probably earlier.

If world-wide correlations on paleomagnetic data prove to be valid, then the lavas of the latter part of the Second Major Eruptive Phase having anomalous or reversed magnetisation may be assigned to a Late Miocene - basal Pliocene period of reversal recognised in France. The normal magnetisation of the Third Major Eruptive Phase lavas may likewise indicate that volcanicity ceased before a period of reversals in mid-Pliocene times.

Earlier concepts of a Late Tertiary peneplain in Eastern Otago require modification. Although a pre-volcanic erosion surface of low relief occurs in the western part of the Dunedin region, the conformable relationship between Waiauan sediments and volcanics in the lower Harbour area rules out the possibility of a peneplain there.

MICROFLORAL EVIDENCE

Subvolcanic and intervolcanic carbonaceous horizons occur at a number of localities in the Dunedin district and offer potential indicators of the duration of the Initial to Second Major Eruptive Phases. Those on which paleobotanical data are available are discussed.

Impure lignite S164/501 and carbonaceous sandstone are exposed on the slopes above the gorge of Millars Creek, 1½ miles WSW of Waitati (S164.2/180858, 1942, not 118858 cf. Couper, 1953, a, b). According to Benson (MS) the lignite occurs in the higher portions of a 300–400 ft thickness of his Older Flood-plain Conglomerate, this being correlated with the period between the First and Second Major Eruptive Phases. Owing to the absence of satisfactory outcrops on the slopes below the lignite, the present writers were unable on a brief visit to confirm the nature of the underlying beds. Some conglomerate certainly overlies the lignite which strikes 0°T and dips 30°E, the comparatively steep dip being no doubt related to deformation on the important fault system which extends along the Waitati Valley.

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*Now at: van Ouwenlaan 24, The Hague, Holland.

Diatomite and leaf beds at Frasers Creek (Kaikorai Valley, S164/128726) are also correlated by Benson with the Older Flood-plain Conglomerate. Lenticular leaf beds occur in bouldery conglomerate in a tributary creek on the north side of the Frasers Gully road. Collection S164/502 examined by Couper (1953 a, b) for microflora was obtained from the main creek bed behind the site of the old swimming baths and here Grange (1930) reports a total thickness of 80 ft of diatomite revealed by boring. This diatomite appears to underlie the conglomerate. Although it is probably of essentially the same age, it is conceivable that the diatomite is older than the conglomerate and available evidence does not rule out the possibility that the diatomaceous beds rest directly on Caversham Sandstone which outcrops in the Kaikorai Valley nearby.

Couper (1953b, p. 14) tentatively placed the Waitati lignite in the Taranaki Series (Upper Miocene) but noted that "dated Opoitian and Waitotaran floras have not been examined and the above beds may be lower Wanganuian in age." In another paper (Couper, 1953a) he gave the age of both the Waitati lignite and the Frasers Gully plant beds (Kaikorai Leaf Beds) as Upper Taranaki or Lower Wanganui Series. Subsequently Couper and McQueen (1954, p. 418) listed both floras as Taranaki. Referring to Couper's work on Waitati and Frasers Gully microfloras, Dr W. F. Harris (*pers. comm.*) reports that "the suggested Taranaki age appears to be based on the assumption that the beds are post-Southlandian owing to unconformable superposition on the Waiauan Dowling Bay Limestone (an assumption now shown to be invalid) and is a preferred choice between Taranaki and Wanganui series rather than between Taranaki and Southland which would seem to be equally possible on the evidence of pollen alone."

Carbonaceous, tuffaceous mudstone (S164/530) is interbedded with volcanic conglomerate on the banks of the Leith two chains downstream from the Union Street Bridge near the University of Otago (Park, 1904, p. 428). It was tentatively mapped by Benson (MS) as younger Floodplain Conglomerate, that is, post-Second, pre-Third Major Eruptive Phase. Although clearly underlying basalt according to Park's description, the occurrence is isolated from the more distinctive marker flows of the Dunedin district. This material has been examined by Dr W. F. Harris (*pers. comm.*). It yielded a microflora similar to that reported by Couper from Waitati and Fraser's Gully (S 164/501–502) except for the occurrence of a *Polypodiites* which is a good match on sculpture with *P. perverrucatus* though rather smaller, and *Nothofagus* comparable to *N. spinosus*. *Polypodiites perverrucatus* is known from Hutchinsonian to Waiauan, and *N. spinosus* is also suggestive of a Waiauan age. On this evidence a large part of the volcanic activity may have been completed in Waiauan time. On the other hand an undescribed pollen species is present which was first noted elsewhere in an Opoitian sample from Kaaua Creek (N 51/9).

More definitely correlated with a younger flood-plain conglomerate is a leaf-bearing horizon reported from Pine Hill from which Oliver (1936,

p. 284) identified "A large leaved *Coprosma,* close to *C. vulcanica* Oliver, of the Upper Pliocene." This has little significance for correlation purposes.

At Waikouaiti North Head, leaf impressions (S155/504) occur within a rhyolitic pumiceous ash first reported by Park (1904, p. 423) consisting of glass (RI. 1.465–1.485) and rare microphenocrysts of alkali feldspar ($Ab_{73}Or_{27}$) and very rare plagioclase. The silica content is 73%. It overlies a basal grit containing a variety of fine-grained basalt and trachyandesite pebbles resting on Caversham Sandstone. At higher horizons in these Waikouaiti Leaf Beds are conglomerates containing basalts, phonolites and basanites (Park, 1904, p. 425) including distinctive porphyritic vitrophyric basanite, virtually indistinguishable from one described by Benson (MS) from Brinns Point, 4 miles to the SSE. In a general way the phonolite pebbles match the typical Waitati phonolite which is taken to mark the end of the Middle Sub-Phase of the Second Major Eruptive Phase over much of the Dunedin district. Many of the Dunedin basanites, including the Brinns Point rock, also appear to belong to the Second Major Eruptive Phase, and the Waikouaiti Leaf Beds are thus fairly satisfactorily dated as not older than the later part of the Second Major Eruptive Phase. A peaty, sponge-spicule-bearing fossil soil (S156/505) overlies the leaf beds and directly underlies ?Third Phase basalt capping the hill. Dr Harris reports that the microflora from this material was poor and not datable.

In summary it may be stated that present microfloral evidence is indecisive but is suggestive of: (a) a Waiauan to Opoitian age for two collections (S164/501, 502) correlated with the Older Flood-plain Conglomerate or an earlier volcanic horizon; (b) a Waiauan to Opoitian age for the Union Street Bridge flora, tentatively correlated with the younger Flood-plain Conglomerate.

Dr Couper has recently (August, 1958) examined plant microfossils from a carbonaceous diatomite collected by Mr F. R. Gordon from Foulden Hills, near Middlemarch, and with the permission of the Director, N.Z. Geological Survey, his report is here published as an appendix. The flora is suggestive of a Taranaki (Upper Miocene) to Waitotaran (Upper Pliocene) age and is compatible with the inference that the associated basaltic rocks are of generally similar age to those in the Dunedin district.

GEOMORPHIC EVIDENCE

Boulders of Third Phase phonolite are the main component of a series of soliflual deposits separated by shaved surfaces and of increasing degree of alteration exposed in a road cutting near the Mount Zion quarry, old Main North Road (Mr J. D. Raeside, *pers. comm.*). This phonolite is evidently pre-late Pleistocene in age. No evidence is known to the writers of any Pleistocene volcanic activity in the Dunedin district.

Even massive phonolites of the Third Major Eruptive Phase are deeply weathered as is shown by cuttings on the new Northern Outlet. Dissection is deep and the volcanic massif as a whole appears to be in a condition corresponding to the residual mountain stage as defined by Kear (1957), while some minor individual centres such as Little Papanui Cone and Harbour

Cone appear to be in the skeletal stage. It is conceivable that massive, rather flatly-topped phonolite ridges such as those forming Wetherston Hill, Mt Kettle and the slopes above Doctors Point, may be remnants of thick, late phonolite coulees, but with these possible exceptions the general lack of constructional volcanic land-forms supports the inference that volcanic activity was complete by a date not later than early Pleistocene, and very likely earlier.

Paleomagnetic Data

Roche (1951) has indicated that flows and dykes in the Auvergne erupted during the Pontian, correlated by Finlay (1947) with the Upper Taranakian (Kapitean), have reverse magnetisation and that this stage continued into the basal Plaisancian (basal Pliocene). Another period of reversal was reported for the basal Pleistocene. Den Boer (1957) suggests that palaeomagnetic observations on the Coiron plateau are compatible with Upper Miocene, Middle Pliocene and Piocene-Pleistocene periods of reversal, with periods of normal magnetisation intervening in the Lower and Upper Pliocene.

In the Dunedin district, all lavas tested from the First Major Eruptive Phase, and from the Early and earlier part of the Middle Subphases of the Second Major Eruptive Phase as defined by Benson (1959, and MS) show normal magnetisation (Coombs and Hatherton, 1959). Flows from No. 21 upwards in the North Head sequence as described by Marshall (1914), and other flows correlated with the upper part of the Middle Substage and with the Late Substage of the Second Major Eruptive Phase show reverse or anomalous directions of magnetisation. Basalts and phonolites tested from the Third Major Eruptive Phase have magnetisation of normal sign.

The earlier normal period (First and early Second Phases), has been dated above as beginning in the latest Middle, or early Upper Miocene. The period of reversal may possibly correlate with the Late Miocene to basal Pliocene reversal postulated by Roche, although it could also have occurred earlier within the Upper Miocene. On the basis of den Boer's suggested mid-Pliocene reversal, it can be stated that there is no paleomagnetic evidence of the Dunedin activity continuing into mid-Pliocene times, and certainly no evidence of activity continuing to the postulated early Pleistocene period of reversal.

Much remains to be done before world-wide paleomagnetic correlations can seriously be attempted for the Upper Tertiary, but an increasing body of evidence supports the validity of the lower Pleistocene reversal and goes some distance towards locating it on the geological time scale. Thus Roche (1956) finds that reverse magnetisation of lavas of Auvergne and Velay prevails from Villefranchian (Upper Pliocene) into Cromerian (Gunz-Mindel interglacial) or slightly younger time, and Akopian (1958) finds that the youngest reverse magnetised flows studied from Armenia are again of Gunz-Mindel interglacial age, the oldest normal flows being Riss-Würm. The above comments are made to demonstrate the potential value of such reversals as world-wide datum planes, should they be confirmed by concordant results in different parts of the world.

PALEOGEOGRAPHIC IMPLICATIONS

The Shore Line in Early Volcanic Times

The Waipuna Bay Formation is clearly of shallow water origin, and it may be inferred that the shore line at the onset of volcanic activity was somewhere near Blanket Bay. At Maori Pa Point near the south-east extremity of Otago Peninsula, water-sorted palagonitic basalt tuffs, well exposed at low tide, are overlain by 50 ft or more of slaggy olivine-rich basalt flows and scoria containing pillow-like forms in various stages of perfection. The "pillows" are separated by a matrix of hard sandstone consisting essentially of quartz with albite and muscovite and a carbonate cement. Sandstone sometimes forms a core to the pillow-like structures, the lava apparently having wrapped around it. It also penetrates contraction cracks in the lava and forms the matrix to basaltic cinders. Although these structures lack the perfection of typical pillows, there is little doubt that the basalt is subaqueous in origin. Unless the sandstone is of fresh-water origin it may be concluded that at an early stage of the First Major Eruptive Phase, to which the Maori Pa Point rocks belong, the sea had not retreated from this part of the Otago Peninsula.

At a date corresponding to the upper horizons of the Waipuna Bay Formation, we may picture a small volcanic archipelago or system of peninsulas, consisting of trachyte flow-rocks and breccias, and early basaltic cinder and scoria cones, lying at the seaward edge of a coastal strip of Upper Cretaceous and Tertiary sediments with a hinterland of schist. Pockets of sediments collected between the volcanics.

The Late Tertiary Peneplain Concept

The concept of an extensive Late Tertiary peneplain in Otago was first put forward by Benson (1935) although earlier workers had suggested Late Tertiary erosion or peneplanation in parts of the province. For instance, Service (1934) had shown that there was in the Goodwood district of North-east Otago clear evidence of an erosion break between the Tertiary sediments and the later Tertiary volcanics, and Benson, Bartrum and King (1934) had maintained that the accordance of summit levels in Fiordland as well as the truncation of the folded Mid-Tertiary sediments in western Otago, was evidence for a peneplain or "matureland" which they suggested was of Late Tertiary age.

The main evidence cited by Benson (1941, Fig. 2) for the existence of a Late Tertiary erosion surface in the vicinity of Dunedin was that the volcanic rocks overlap progressively westwards on to older sedimentary formations. They rest on the Waipuna Bay Formation in the Dowling Bay and Blanket Bay inliers, on Caversham Sandstone in the belt from St Clair to Caversham to Waitati Valley; and on Abbotsford Mudstone in the belt Saddle Hill to Abbots Hill to Double Hill, lines respectively 5 and 7 miles WNW of Dowling Bay. Further in the same direction, some volcanic outliers rest directly on quartz grits of the Taratu Formation (Piripauan to Haumurian) or on the basement schists although in most cases there is at least a thin veneer of sediments, indicating that pre-volcanic erosion failed to lay bare the schist undermass over large areas of Eastern and eastern Central Otago. The inferred late Tertiary erosion surface was thought to be sufficiently mature to warrant the term "peneplain".

It is now established that there is a conformable relation between marine sediments and volcanics at Dowling Bay and Blanket Bay (Coombs, White and Hamilton, 1960). A post-Waiauan, pre-volcanic peneplain does not exist in these areas. Nevertheless an erosion surface between the volcanics and the Tertiary sediments on the west side of Dunedin is unquestionable. Here it is impossible to estimate the amount of pre-volcanic erosion since it is not known whether sedimentation continued up to the Waiauan or ceased with the deposition of the Caversham sandstone of Hutchinsonian (Upper Oligocene) age. It is even possible that the whole of the erosion took place after the initiation of volcanic activity in the lower Harbour area centred on Port Chalmers and Portobello. Except perhaps for trachyte tuffs resting on Caversham sandstone at Burns Creek, trachytes that can convincingly be correlated with the Initial Eruptive Phase are confined to an area east of the line Maori Pa Point - Blanket Bay - Purakanui whilst lavas of the early Subphase of the First Major Eruptive Phase barely spread beyond these limits. Westward thinning of the Tertiary Marine formations would allow overlap of volcanic rocks on to older and older sediments without the intervention of large scale erosion.

On the other hand erosion may have begun soon after Hutchinsonian times thus allowing sufficient time for the formation of a local peneplain in the inland zone before the Waiauan.

Evidence for relief in this erosion surface can be seen on the cliffs between St Clair and Blackhead, in an irregular lower surface to the volcanics capping Clarendon Hill (Dr H. W. Wellman, *pers. comm.,* cf. map in Macpherson, 1945) and elsewhere. It is clear that Benson himself recognised that some relief existed on the immediately pre-volcanic surface. Thus, referring to his Moderately Deformed Region peripheral to the Dunedin district he wrote (1942, p. 87) "It seems probable, however that *in general* the lavas were poured out over surfaces *usually of low relief.*" (our parentheses). The present authors are in complete accord with these conclusions. As long as the existence of such relief is recognised the description of the surface as a peneplain or erosion surface ceases to be a matter of key importance. On present evidence the authors prefer the latter term.

It is important to stress that the existence of such pre-volcanic relief, possibly of up to a few hundred feet, implies that relief in the present basal surface of the volcanics does not in itself constitute adequate evidence of post-volcanic deformation in Eastern Otago.

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APPENDIX

PLANT MICROFOSSILS FROM THE MIDDLEMARCH DIATOMITE

By R. A. COUPER

Material examined

Carbonaceous diatomite from 10 ft below ground level and over 140 ft above schist basement from a diatomite pit on Foulden Hills Station (grid. ref. S154/907135) was collected by Mr F. R. Gordon, Ministry of Works, Dunedin, during the course of an investigation of the Middlemarch diatomite.

The sample S154/501 (L 1085) yielded a plant microfossil flora rich in specimens but poor in species.

Age

Among the 26 species identified, *Nothofagus cranwellae* Couper, *N. matauraensis* Couper, *Triorites harrisii* Couper, *Cupanieidites orthoteichus* Cookson and two undescribed new species of dicotyledonous pollen grains all make their last appearance in beds of Waitotaran (uppermost Pliocene) age. Only a few species were identified which enabled a lower age limit to be assessed. They included an undescribed new species of proteaceous pollen known elsewhere in New Zealand only from the Taranaki Series (Upper Miocene) and Opoitian (Pliocene).

Available evidence suggests a Taranaki (Upper Miocene) to Waitotaran (Pliocene) age. Comparable floras are known from impure lignites and tuffaceous carbonaceous silts interbedded with basic volcanic rocks in the Dunedin district (Couper, 1953 a, b).

Vegetation and Climate

The flora is dominated by pollen grains of at least two species of the *Nothofagus brassii* group of beeches. Judging by the abundance and widespread distribution of their pollen grains this group of beeches was a dominant element in the Tertiary flora of New Zealand from the upper Eocene onwards. They became extinct in New Zealand at the end of the Pliocene but are still living in New Guinea and New Caledonia.

Other species identified include *Cupanieidites orthoteichus,* the pollen of an extinct member of the tribe Cupanieae of the family Sapindaceae and *Dysoxylum spectabile* Hook. f. (kohekohe). The Cupanieae have their greatest development in tropical and semitropical rain forests. They have no living representatives in New Zealand. *Dysoxylum spectabile* is a common coastal tree in the North Island but extends today only as far south as Marlborough.

The presence of the above warmth-loving plants in the sample clearly indicates that the climate at the time of deposition of the diatomite was warmer than that of the present day.

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THE TYPE LOCALITY CONCEPT IN TIME-STRATIGRAPHY

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Abstract

The significance of type localities in time-stratigraphic concepts is investigated drawing examples from microfaunally based New Zealand Tertiary Stages. The composite nature of some stage definitions makes it clear that type localities do not hold a central position in the concept of these units, which are by nature homotaxial and rely on simple inductively-based inferences drawn from many sections. Apart from their function as name bearers, type localities are conceded no special importance, and definitions framed solely in terms of them are considered to be inadequate for the working of a homotaxial system.

Appraisal of the rapidly expanding literature on time-stratigraphic classification reveals the presence of at least one common theme: the necessity of the type locality. The American Commission on Stratigraphic Nomenclature (1952, p. 1629) writes: "Time-Stratigraphic units are material units, each of which compasses all the rocks formed in an interval of geologic time defined by the beginning and ending of deposition or other mode of origin of those rocks contained in the type section or otherwise designated type of the unit." Hedberg, whose writing has strongly influenced time-stratigraphic thinking, has insisted that "A time-stratigraphic unit, just like any other kind of stratigraphic unit, must be referable to type or reference sections of rock strata if it is to mean anything" (1958, p. 1890). Indeed the type section is crucial to Hedberg's concept of a time-stratigraphic unit. He is emphatic (1958, p. 1890) that the scope of a stage away from the type section is definable," . . . only to the degree that isochronous surfaces coinciding with the boundaries of the stage in the type section can be traced or identified from that type section."

Recently, however, views clearly divergent from those of Hedberg and the American Commission have been expressed by two American stratigraphers. Wilson (1959, p. 777) maintains that, "An appeal to what is found at the area that was accidentally described first will no longer work. Let us recognise type sections for what they really are, samples." Another Texan stratigrapher, W. C. Bell, advances essentially the same concept, thus (1959, p. 2863–4) "No *place* is typical of a *time* and only events whose consequences are evident over wide areas are potential elements in the historical time scale." Bell further makes the point that application of the law of priority to time-stratigraphic nomenclature stabilises only names and not the concepts the name stands for. In view of these opposing opinions, it seems appropriate to make some analysis of local concepts and practice in order to judge the significance of type localities or sections in New Zealand Tertiary time-stratigraphy.

In New Zealand, the importance of type localities and of reasonable application of the law of priority were asserted by Thomson (1916) in his original formulation of the basis of the modern scheme of Tertiary time-stratigraphic classification. However, Thomson did not always cite specific sections as types; rather, he attached his names to well known lithologic units, e.g., Ototaran for the time represented by the Ototara Limestone. Precision in definition was not attempted, no doubt because of the undeveloped state of paleontology at that time.

Allan (1933, p. 83), however, found that, "there must be a more rigorous definition of stratigraphical units" and proceeded to cite rock units in particular sections as types for Tertiary stages. These type sections clearly came to occupy a central position in Allan's stage definitions: "The Awamoan stage may be defined as the interval of time represented by the deposition of beds (a) to (i) in the standard section at the Rifle Butts, Oamaru, and as well as such periods as may be represented therein by non-deposition or erosion." Faunas characteristic of the type section were cited. It is apparent that the concepts embodied in this paper closely approximate those expounded more recently by Hedberg and the American Commission.

In proposing Opoitian, Kaiatan and Whaingaroan stages, Finlay (1939) used Allan's form of definition; yet there are signs of a change in concept, and the type section was clearly coming to occupy a position of lesser importance. Finlay's diagnosis of Whaingaroan included citation of an assemblage characteristic of the stage (not necessarily the type locality), and concluded that the stage was also characterised by ". . . the absence of *Cibicides parki, Globigerinoides* and *Globigerina triloba.*" Finlay here had the concept of a Whaingaroan fauna which he found widespread in New Zealand and which was distinct from assemblages assigned to his Kaiatan by the absence of certain species and the incoming of others. Yet this was not directly discoverable at the type locality of the Whaingaroan Stage because the Whaingaroa Beds directly overlie a non-marine sequence.

In the following year Finlay and Marwick (1940, p. 100) asserted essentially Thomson's philosophy: "The terms type section and type locality . . . should be rigidly applied, permanent, and reasonably subject to the law of priority." However, their faunal lists show that in point of fact their concept of most stages was based upon knowledge not wholly to be gained from the type locality. An outstanding example is the key fauna listed for the True Hutchinsonian: 144 names (Mollusca, Brachiopoda and Foraminifera) were cited, yet only 18 of these were known at the type locality. That Finlay and Marwick (1947) drastically revised their conception of Hutchinsonian and Awamoan is not pertinent to this argument; the essential point to be established is that in this paper they applied the same broad working definitions of time-stratigraphic categories that Finlay (1939) had initiated in his stage proposals. In practice, therefore, type sections were in several instances little more than name-bearers and it appears to be to this end that Finlay and Marwick urged strict application of the terms "type section" and "type locality."

A new form of definition was used by Finlay and Marwick (1947) for the additional stages then erected. The Otaian, for example, was defined as ". . . the sediments deposited from the first appearance of the Otaian fauna (as judged from the type locality) to the first appearance of the Hutchinsonian fauna . . . It is defined as that part of the section whose lower limit is marked by the lowest occurrence of (primarily) *Ehrenbergina* and (secondarily) *Spiroloculina novo-zealandica* Cush. and Todd . . . and whose upper part is marked by the continued presence of *Plectofrondicularia proparri* Fin., *Haeuslerella hectori* Fin. and *Textularia pseudomiozea* Fin. (instead of *P. parri* Fin., *Haeuslerella pukeuriensis* Parr., and *Textularia miozea* Fin. of the Hutchinsonian), and by the absence of *Virgulopsis pustulata* Fin. s. str." Hedberg and the American Commission would regard this definition as that of a biostratigraphic, not time-stratigraphic, unit; practically however, certain biostratigraphic units are given time significance and only a pedant would insist on the necessity of Allan's form of definition.

Finlay and Marwick's (1947) stage proposals, as they read, seemingly strongly emphasise the centrality of the type section in their time-stratigraphic concepts. However, as in their earlier paper (1940), it can be shown that, at least in some instances, knowledge drawn from rock columns other than that of the type to a large extent moulded their diagnoses. Consider the Otaian: re-examination of Finlay's mounted slides upon which he based his knowledge of the microfaunal sequence of the type locality shows that he had not found the cited primary index *Ehrenbergina* at Bluecliffs; moreover, recent re-sampling of the section showed, as do Finlay's slides, that *Plectofrondicularia proparri* is not continuously distributed through the section, and that *Textularia pseudomiozea* occurs only near the base of it. These statements must not be construed as casting doubt upon the accuracy of Finlay and Marwick's definition; what requires to be established is that this definition is composite, an understanding not clearly implicit in the wording. The definition is clearly an amalgam of knowledge obtained primarily from many east coast South Island sections where Finlay had repeatedly found the microfaunal sequence described in his definition of Otaian – such was his belief in the stability of this sequence that he was able to define the lower limit of the Otaian at its type locality upon a genus he had not found there. Subsequent work has shown that he was correct in assuming that *Ehrenbergina* occurred at Bluecliffs and that his failure to discover it was due to the widely spaced samples he had to use for his knowledge of the section.

The excellent working definitions of Tertiary stages given by Hornibrook (1959) are similarly composite. In a discussion of the Waitakian stage, he says, "The upper limit of the stage is marked by the last occurrence of *Cibicides thiara* (Stache) and *Gyroidinoides allani* (Fin.), and extends to just below the level at which *Spiroloculina novozealandica* Cushman and Todd and *Ehrenbergina* spp. appear." This information is not based either on Otiake section, where Otaian has not been recognised, or on Bluecliffs where *C. thiara* and *G. allani* do not occur, but rather upon such rock columns as Weka Creek, North Canterbury, All Day Bay, North Otago, and several in North Taranaki - Te Kuiti where Otaian index species appear sequentially to the outgoing of Waitakian key species.

The examples already considered serve to make clear the working basis of the stratigraphic scheme developed by Finlay and Marwick from the foundations laid by Thomson. Thomson (1916, p. 39) had urged the discovery of, " . . . fossils which are at least moderately abundant and yet restricted in range." Finlay and Marwick found that patterns of local entrants and extinctions (chiefly smaller Foraminifera) were repeated in the same order in geographically separate rock columns. Certain of these elements were segregated as "Key Species", and the overlapping of these ranges forms the working basis of Tertiary time-stratigraphic units. The author considers that the scheme does not simply depend upon the method of deductive testing advocated by Popper (1959), whereby the fauna of the type locality is taken as the basis of a hypothesis of sequential order upon which attempts at falsification are made by examining faunal sequence in other rock columns; for Popper's method does not cover the point about which we are primarily interested – the setting up of the hypothesis. Rather it appears that our time-stratigraphic scheme is one of inferring sequential order on this basis: if species A has always been found to disappear from a rock column before the incoming of species B, and there is no known case of species A and species B occurring together, then it is probable that on the next occasion A is found, B will occur higher in the section and that this probability increases with the number of sections in which the sequence A followed by B has been observed. Thus for example as more instances accumulate wherein *Cibicides thiara* is found to disappear from a rock column before the entry of *Ehrenbergina*, increasing confidence is felt in the concepts of Waitakian and Otaian as sequential stratigraphic units.

New Zealand Tertiary time-stratigraphic units may thus be considered to be a system of inductively based inferences as to the sequential order of certain biological groups: time significance is granted to these units, but in fact only a homotaxial relation is demonstrated. However, if inductive inference is basic to the working of time-stratigraphy, the validity of this method requires some comment. Russell (1948), accepting the work of Keynes (1921), shows that in the case of inductions of the type, "all A is B" the probability (p_o) that this is so in advance of observed instances must be finite for, according to Keynes, p_n, the probability of the generalisation after n instances, can move towards 1 as a limit only if the ratio q_n to p_n (q_n is the probability that we should have observed the n favourable instances and no unfavourable instances if the generalisation were false) tends to zero as n increases. But induction in itself cannot show when this condition is satisfied, and some outside principle is required which grants to certain generalisations a higher initial probability than that which relates to wholly random generalisations. The postulate of "natural kinds" (Keynes postulate of limited variety) has ready application to the philosophy of speciation where evolutionary theory provides a basis for certain character groups to exhibit greater stability than others. However, New Zealand Tertiary Stages primarily depend upon combinations of local observed stratigraphic ranges of selected species, and the writer is not aware of any principle which would give an *a priori* basis for certain combinations to be more stable than others. A time-stratigraphic classification based upon S. H. Tan's scheme (1939) of combinations of evolutionary lines may perhaps be more amenable to the doctrine of "natural kinds."

As there is at present no outside principle to provide a basis for inductive inference as applied to time-stratigraphic classification it is likely that the instability which has characterised classifications in the past will continue as further inductively based inferences have to be disallowed. A recent instance is Hornibrook's discovery (1959, p. 428) that the ranges of *Loxostomum truncatum,* Waiauan index, and *Bolivinita quadrilatera,* a lower Tongaporutuan marker, overlap in some sections in southern Hawke's Bay; such an observation will no doubt lead to a reformulation of these two units. Recognition of the instability inherent in time-stratigraphic systems because of their use of simple inductively-based inferences, suggests that time-stratigraphic divisions form units unsuitable for purposes of basic field mapping.

In review, it is clear that although New Zealand workers have stressed the importance of type localities, the system constructed by Finlay and Marwick rests upon a much broader basis; while geologic time units *per se* may require type sections, those time-stratigraphic units which have solely a biologic basis must incorporate into their definitions information from as many rock columns as possible, and the only special function that attaches to the type locality is that of name bearer. To define such a time-stratigraphic unit in terms of one section is to refuse to take cognisance of the methods by which a homotaxial system is worked. To this extent the theoretical system proposed by Hedberg and the American Commission appears divorced from working practice, and the criticisms of Bell (1959) and Wilson (1959) are timely.

ACKNOWLEDGMENTS

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BASE METAL AND GOLD-SILVER MINERALISATION ON THE SOUTH-EAST SIDE OF THE AORERE VALLEY, NORTH-WEST NELSON

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Summary

Geological mapping in the Aorere Valley, north-west Nelson, has resulted in an interpretation of the Aorere-Haupiri contact as a low angle thrust plane. The mineralisation, closely related to the metamorphism, is concentrated along this contact. Where the contact is anticlinal it is the point of greatest concentration and has been the site of old mine workings, especially Johnston's United Mine. It is suggested that metasomatic solutions have been particularly active at the front of a deep-seated advancing nappe fold. The economic implications of this structural concept and mineralisation are significant and the possibility of hidden ore bodies is considered.

INTRODUCTION

Johnston's United, Phoenix, Ophir, Richmond Hill, Redhill and Coppermine are five old mines located in lower Paleozoic metamorphic rocks on the south-east side of the Aorere Valley (Fig. 1), between two and four miles from the township of Rockville (N.Z.M.S.I. Sheet S3). The regional geology, mineralisation and mining history have been described by Bell (1907, p. 17, 94–97). Recently the writers re-examined the area to determine the nature of the sulphide mineralisation, the structural, stratigraphic and other factors controlling the distribution and extent of the mineralisation, the origin of the ore-bodies, and the possible economic value of the deposits in the district.

Of the six mines in the district only the Johnston's United Mine was worked economically for any considerable period. Between 1879 and 1897 the Johnston's United Company recovered 20,000 oz of gold (Bell, 1907, p. 94). The richest part of the mine was a limonitic cap (gossan) and oxidised zone near the surface. Below the oxidised zone a zone of secondary enrichment contained both primary and supergene sulphide minerals – galena, sphalerite and chalcopyrite. The sulphide minerals were dumped on a spoil heap outside the entrance to the drive, where good specimen chalcopyrite and galena ore may still be collected. At present only the Johnston's United Mine can be entered; the other mines have completely caved in.

GENERAL GEOLOGY

Metamorphic rocks of the Haupiri and Aorere Groups are present on the south-east side of the Aorere Valley in the Johnston's United - Richmond Hill area. The Haupiri rocks were recognised by Bell (1907) only as rather narrow lenses of volcanic conglomerate and breccia, as are typical of the

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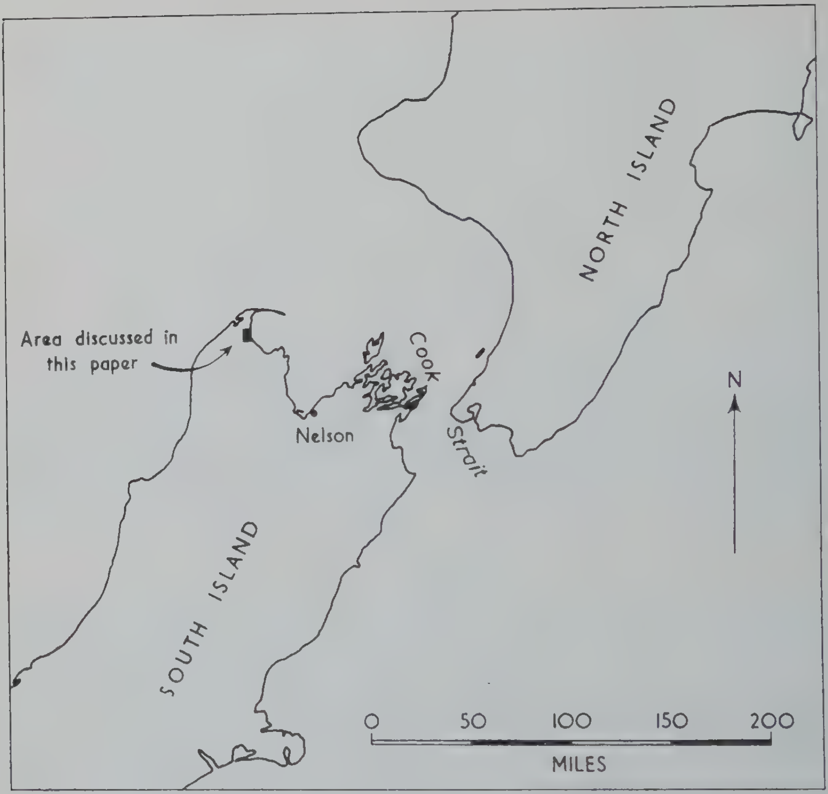

FIG. 1—Locality Map.

Haupiri rocks in their type area – the Haupiri Range – nine miles to the south. The bulk of the rocks considered Haupiri by the writers were mapped as Aorere Series – crystalline schists and quartzites – by Bell. Complete revision of North-west Nelson lower Paleozoic stratigraphy and structure is now in progress in conjunction with the New Zealand Geological Survey's 1 : 250,000 Geological Map project, and will be presented shortly (Grindley, in press). It is not proposed at this stage to explain new stratigraphic interpretations or structural concepts except insofar as these affect the nature and location of the mineralisation. Broadly, it is believed from regional mapping to the south of this area, where the Cambrian-Ordovician succession is less metamorphic and structurally simpler, that the lower Paleozoic sequence on the south-east side of the Aorere Valley is inverted, Haupiri rocks of Cambrian age resting on Aorere rocks of Ordovician age. The Haupiri-Aorere contact is thus interpreted as a major low-angle thrust plane, the Haupiri rocks as downfolded remnants of an extensive, probably recumbent, overthrust sheet (Haupiri Nappe), and the Aorere rocks as the autochthonous floor (essentially *in situ*) across which the Haupiri nappe-sheet was thrust. The direction of tectonic transport was from south to north. This direction is at right angles to the east-west lineations observed in both Haupiri and Aorere schists, and in accordance with north-verging drag folds in the uppermost part of the Aorere autochthon. Mineralisation on the south-west side of the Aorere Valley is concentrated along the thrust-plane at the contact of the Haupiri and Aorere rocks, and is obviously closely related, as is the metamorphism, to the major tectonic transport of the Haupiri nappes across the area in a northerly direction. Nappe movements, metamorphism and mineralisation are believed to have taken place in lower Paleozoic time, and to be earlier than the intrusion of granitic stocks and batholiths in the later Paleozoic.

In the early Tertiary (Eocene – lower Oligocene) the south-east side of the Aorere Valley, in common with the rest of North-west Nelson, formed part of a widespread peneplain that extended over much of the South Island. During peneplanation, the basement rocks were levelled to a near-level surface, were deeply weathered and subsequently covered by quartzose coal-measures and marine sandstone, limestone, and later, in Miocene times, by massive deep-water mudstones. In later Tertiary and Quaternary times, the area was elevated by block-faulting, the Tertiary sedimentary cover removed, and the early Tertiary peneplain re-exposed over large areas. Erosion controlled by fluctuating Pleistocene sea-levels has carved deep youthful gorges into the peneplain surface, but has not destroyed the surface in intervening areas. Outliers of quartzose coal measures and small buttes of limestone show that the peneplain surface is still intact over large areas.

MINING

The richest of the old mines – Johnston's United – is located at the intersection of the Haupiri-Aorere thrust-plane with the early Tertiary peneplain. Johnston's United has an extensive "gossan" or limonitic cap, produced by long-continued and extensive weathering of the ore-body during lower Tertiary peneplanation. Surface oxidation and formation of gossan was accompanied by a "zone of secondary enrichment" directly below, and underlain at deeper levels by primary ore of lower grade (See Bell, 1907, p. 95). The richest gold values at Johnston's United were found in the gossan cap, and the richest base-metal values – Lead-Zinc-Copper – in the underlying zone of secondary enrichment.

Of the other five mines, only the Phoenix and Richmond Hill mines were visited. The Phoenix Mine is completely caved in and little can be learnt from the workings. Apparently the mine was a low-grade gold prospect. Richmond Hill attracted considerable attention when first discovered in 1873 because of the occurrence of rich silver ore. The argentiferous quartz veins cut Haupiri amphibolites and granitic rocks in a gorge of the Parapara River, a few yards downstream of the near-vertical Haupiri-Aorere contact. At Johnston's United the same contact dips gently east, showing that the Haupiri Nappe was folded into an asymmetric syncline, prior to Tertiary peneplanation. The workings of Richmond Hill mine are not accessible, although a later drive can be examined. The old mine was worked from a shaft, which was used by later prospectors for disposal of spoil from the drive, and so cannot now be examined. It seems from the report of Bell (1907, p. 97) that the mine was prematurely abandoned for financial reasons at a depth of 106 ft, where the lode was 5 ft wide and carried both pyrites and argentiferous galena with a silver content varying from 22 oz to 51 oz to the ton. The lode was capped by a gossan at the surface. For a complete account of the mining operations in the area see Bell (1907, p. 17).

LITHOLOGY AND PETROGRAPHY

*Aorere Group**

The rocks lying below the ore body at Johnston's United mine and east of the Richmond Hill quartz veins were mapped as a metamorphic part of the Aorere Series by Bell (1907) and considered Ordovician or earlier. They consist of fine-grained, graphitic phyllites and low-grade schists, schistosity increasing slightly towards the thrust plane at the base of the Haupiri. The rocks have a lithology similar to the graptolite-bearing upper Ordovician Mount Arthur argillites at the head of the Cobb Valley, 20 miles to the south, and are probably of the same age. Recent mapping has shown that graphitic argillites and phyllites can be traced as a continuous belt from Cobb Valley to the south-east side of the Aorere Valley. The nearest fossils are upper Ordovician graptolites on the south side of the Lead Hills granite boss, ten miles to the south. Graptolites were recorded from the Perseverance Mine (old name for Johnston's United) by Benson (1936, p. 360). This record was based on specimens believed to have been taken from the Perseverance Mine in 1866. No further specimens have been discovered in later mining or geological examination.

Haupiri Group

The rocks lying above the ore body at Johnston's United mine are medium-grained micaceous schists, some typical mineral assemblages being as follows: quartz, muscovite, chloritoid (K feldspar); quartz, muscovite, biotite (garnet); quartz, biotite, muscovite (K feldspar, chlorite); quartz, K feldspar, biotite, muscovite (chlorite); quartz, K feldspar, biotite, muscovite (albite, calcite). The schists contain up to 2% opaque ore minerals. The Haupiri schists were described as amphibolitic schists by Bell (1907, p. 94) who noted the relationship of the various ore bodies to the contact between the graphitic and amphibolitic schists, as had been mentioned earlier by Cox (1882, p. 71) and Hutton (1871). No amphibole mineral is present in the sections examined, but other Haupiri rocks contain abundant amphibole. The presence of chloritoid is significant, as this mineral is commonly found in rocks that have undergone considerable shearing. The petrography of the Haupiri schists is in accord with their derivation from pyroclastic and volcanic flow rocks, the chief lithology in the type section of the Haupiri Group of the Haupiri Range nine miles to the south. The Haupiri pyroclastics are generally massive without visible bedding; this also applies to the schists overlying the ore body at Johnston's United. Surrounding the old Richmond Hill Mine, the Haupiri rocks are partly amphibolitic and feldspathic schists and partly dioritic and granitic rocks. The granitic rocks are exceptionally fine-grained, poor in dark minerals and are most probably of metasomatic origin. It seems probable that metasomatic solutions would be particularly active at the front of a deep-seated advancing nappe-fold. The argentiferous quartz veins conform to the contacts of granitic segregations with graphitic schists.

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*The name Aorere is used here in the sense employed by Bell (1907) as a broad grouping of Ordovician rocks. Aorere Group now covers only lower and middle Ordovician rocks and the name Golden Bay Schists has been given to these low-grade graphitic schists (see Grindley, in press).

MINERALISATION

All the mineralised lodes in this area occur along or near the Haupiri-Aorere contact (Fig. 2). In the Johnston's United Mine the lode runs directly along this contact. The lode formation is generally between 1 ft and 2 ft, but is said to have occasionally reached 15 ft in width. Most of the workings in the mine were not accessible because of rock falls. It was noted, however, that the most extensive workings occurred where the Haupiri-Aorere contact was anticlinal.

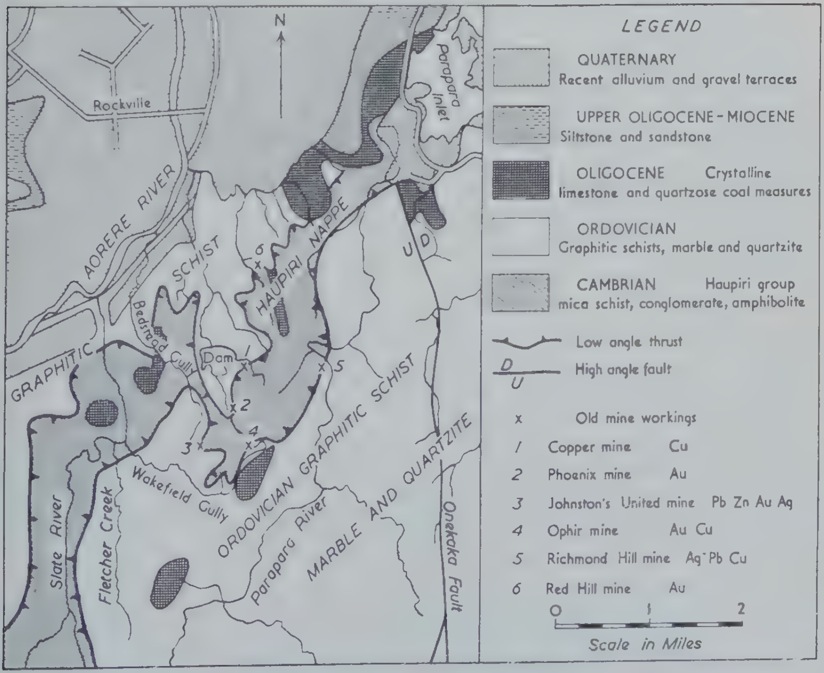
N
Rockville
Parapara Inlet
AORERE RIVER
SCHIST
HAUPIRI NAPPE
6
Bedstead Gully
Dam
1
2
3
4
5
U
D
GRAPHITIC
ORDOVICIAN GRAPHITIC SCHIST
MARBLE AND QUARTZITE
Wakefield Gully
Slate River
Fletcher Creek
Parapara River
Onekaka Fault
LEGEND
QUATERNARY Recent alluvium and gravel terraces
UPPER OLIGOCENE - MIOCENE Siltstone and sandstone
OLIGOCENE Crystalline limestone and quartzose coal measures
ORDOVICIAN Graphitic schists, marble and quartzite
CAMBRIAN Haupiri group mica schist, conglomerate, amphibolite
Low angle thrust
D U High angle fault
x Old mine workings
1 Copper mine Cu
2 Phoenix mine Au
3 Johnston's United mine Pb Zn Au Ag
4 Ophir mine Au Cu
5 Richmond Hill mine Ag Pb Cu
6 Red Hill mine Au
0 1 2
Scale in Miles

FIG. 2—Geological map of the Aorere-Haupiri contact near Rockville, North-west Nelson.

Outcrops of the Johnston's United lode occur a short distance below the surface of the stripped Tertiary peneplain. The oxidised zone extends to approximately 50 ft below the present surface. In this zone hydrated oxides of iron (limonite) are the only ore minerals present, and fill voids in the quartz where minerals have been leached out of the ore. Limonite pseudomorphic after cerussite ($PbCO_3$) is occasionally seen. Most of the other mines in the area have their outcrops below the level of the peneplain and do not contain extensive gossans, and subsurface oxidised and secondarily enriched zones.

The lowest accessible level is approximately 80 ft below the surface. Sphalerite, galena, pyrites, arsenopyrite and minor amounts of chalcopyrite and tetrahedrite were found. An analysis of ore from this level showed 14·2% galena, 33·4% sphalerite, 3 oz, 9 dwt silver/ton and 3 oz gold/ton (Bell, 1907, p. 95). Most of the ore from this level has, however, been mined out. Polished sections of ores were examined and by the nature of replacement textures the order of deposition of ore minerals is considered to have been as folows: Pyrite, arsenopyrite, sphalerite, galena, tetrahedrite, sphalerite, chalcopyrite. The first sphalerite to be deposited is dark brown in colour, thus suggesting a high iron content, a relatively high temperature of deposition, and is thus most probably of primary origin. The later sphalerite is yellow brown in colour, suggesting a low iron content, low temperature of deposition and a supergene origin. The low temperature sphalerite is much more common than the high temperature sphalerite. The chalcopyrite was deposited after the low temperature sphalerite and is thus probably also of supergene origin. Limonitic staining and sugary quartz are present, implying that, in this level, some leaching has taken place.

The lowest level worked is 215 ft below the surface. The drive was filled with water during the writers' visit and could not be examined. Bell (1907, p. 95) states that this level "shows 18 in. of quartz in which occurs pyrite to the exclusion of galena, sphalerite and other sulphides met with above, thus constituting a third zone characterised by what may be termed the lean sulphides."

ORIGIN OF ORE-BODIES

The Johnston's United ore body is located at the intersection of the Haupiri-Aorere thrust plane with the Tertiary peneplain surface. The considerable depth to which leaching has occurred within the lode, suggests that the gossan, and the subsurface oxidised and secondarily enriched zones, were formed during Tertiary peneplanation. The extremely high gold content of the gossan suggests that erosion had proceeded for a long period during which gold was being concentrated close to the surface. The well preserved state of the peneplain indicates that there has been little erosion since formation of the peneplain and practically no possibility of later enrichment of ore at the surface.

The presence of sphalerite of both low and high iron content in the 80 ft level suggests that both supergene and hypogene sulphide minerals are present. The ore in the 215 ft level is most probably entirely of primary origin. Under favourable conditions, primary ore may contain appreciable quantities of galena, sphalerite, arsenopyrite, and tetrahedrite though the overall grade would almost certainly be lower than in the zone of secondary enrichment.

The relatively high percentage of ore minerals present in the Haupiri schists suggests that these rocks are a possible source of the ore deposits. The ore minerals were possibly concentrated in metasomatic solutions formed at the front of the deep-seated advancing Haupiri nappe-fold. The Aorere argillites and slates possibly acted as an impermeable barrier to downward percolating ore-bearing solutions from the overlying Haupiri schists, the carbon content of the Aorere rocks acting as a reducing agent for the deposition of the sulphide minerals. Folding of the Haupiri-Aorere thrust plane produced voids at anticlinal crests where the ore-bearing solutions were precipitated.

Another possible but most unlikely source of the ore minerals is from the Lead Hills granite boss, situated approximately six miles to the southwest of the area. The granite intrudes Aorere rocks close to the thrust-plane contact with overlying Haupiri schists. The zone of contact metamorphism around the granite boss is only a few chains wide and there are no known ore-bearing lodes in the vicinity. The Lead Hills granite is not, therefore, a likely source of the ore minerals.

CONCLUSIONS

(1) The Johnston's United, Richmond Hill and other mines are located on lodes formed along a major thrust-plane at the base of a lower Paleozoic nappe-fold of Haupiri rocks. Tectonic transport was from south to north, and was accompanied by east-west lineations, north-verging drag folds and metamorphism of both Haupiri and Aorere rocks. The ore minerals were probably derived initially from pyroclastics and volcanic flows in the Haupiri Group and concentrated in metasomatic solutions formed at the front of the deep-seated advancing nappe. The ore-bodies are thus considered to be syntectonic deposits related to tectonic movements and regional metamorphism, and unrelated to later intrusion of discordant granite stocks and batholiths.

(2) Primary sulphide mineralisation took place along or close to the Haupiri-Aorere thrust-plane and was concentrated particularly where the thrust-plane had been folded anticlinally during tectonic movements. The lodes were probably formed by downward percolation of ore-bearing metasomatic solutions from the Haupiri schists, and the ore minerals precipitated by carbon in the underlying Aorere graphitic schists.

(3) At Johnston's United and Richmond Hill, a gossan, an oxidised zone and a zone of secondary enrichment were formed during extensive and long-continued peneplanation in the early Tertiary (Eocene – lower Oligocene).

(4) In the accessible part of the Johnston's United Mine the quantity and grade of the remaining ore is too low to be of economic importance. Richmond Hill Mine appears to have been prematurely abandoned while ore values (mainly silver-lead) were reasonably good, and may warrant further consideration. Unfortunately the old workings are no longer accessible.

(5) Similar lodes may be found along the Haupiri-Aorere thrust-plane, especially where this plane intersects the peneplain surface. It should, however, be pointed out that the area has been extensively prospected, and all surface indications, such as gossan caps, have probably been found. If hidden ore-bodies, without gossan caps, exist along the thrust-plane, they are perhaps unlikely to have undergone strong secondary enrichment, and probably will be lower-grade than the ore-body at Johnston's United Mine.

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THE GEOCHEMISTRY OF ALKALI METAL IONS IN THE WAIRAKEI HYDROTHERMAL SYSTEM

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Summary

Chemical analyses show that in the Wairakei hydrothermal field hot chloride water is fed to the levels tapped by the drillholes by at least two separate entries – one near the group of holes in the East, and another West of, or about, the main Western production group. This is in agreement with the results of physical measurements of temperature and pressure in the area.

The changes in concentrations of the various alkali metal ions in the waters can be correlated with their reaction with country rock to form the various zones of hydrothermal alteration found by petrological examination of drill cores.

The chemical results are sufficient to show that all the Wairakei waters are of a common primary origin. The high concentration in the waters of the rare element caesium is evidence that the source of the dissolved chemicals is a high temperature and pressure magmatic steam phase.

The constancy of the chemical characteristics over a period of seven years indicates that the hold-up volume in the Wairakei circulatory system must be large compared with the present total volume drawn from the area by drillholes.

INTRODUCTION

Drillholes in the Wairakei hydrothermal system tap hot water at approximately 250°C, which contains in solution alkali chlorides, silica, carbon dioxide, boric acid, and smaller amounts of sulphide, sulphate, fluoride, and ammonia. A set of papers giving a general description of the chemistry, geology, and physics of the area was compiled by Grange (1955).

A record has been kept of the chemical analyses of waters from the drillholes since mid 1950. The information now available from about 50 holes has enabled a consistent picture to be obtained of the temperature, pressure, and chemical distribution in the Wairakei hydrothermal system. Studt (1958) published the variations in artesian pressure with time and position in the hydrothermal field, while Banwell (1960) gave the comparable temperature distribution pattern.

This paper presents a survey of alkali metal ion analyses which is used to discuss the movement of waters in the Wairakei hydrothermal system. The general geochemistry given for these metal ions includes a discussion of their possible origins in the system, their reaction with the country rocks, and a comparison with their relationships in other hydrothermal areas.

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Mineralogical Background

The observation by Fenner (1936) that sodium and calcium in the feldspars of the country rock from drillholes at Yellowstone National Park were replaced by potassium from ascending hydrothermal solutions is of basic importance to this work.

Steiner (1953, 1955) described the hydrothermal rock alteration found in drill cores from Wairakei. The country consists of porous vitric and lapilli tuffs (the Wairakei breccias) with an interbedded argillaceous formation. The latter (Huka mudstone), which consists of two mudstone members separated by porous breccia, is followed at depth by 1,000 ft, or greater, of the Waiora pumice breccias. This in turn overlies the Wairakei ignimbrite. Steiner showed that as the hot chloride water solutions pass from fissures in the ignimbrite base at 2,000–3,000 ft and rise through the overlying formations of rhyolite and breccias, successive zones of alteration are caused in the rock. In the deepest alteration zones potassium from solution is taken into the country rock with the formation of the minerals hydromica and adularia. Sodium and calcium which are liberated by this replacement process are partly deposited again at intermediate levels as the sodium feldspar albite, and the calcium-rich zeolites, wairakite and ptilolite.

Some further chemical analyses of cores taken from drillholes at Wairakei are presented for comparison with the petrological results of Steiner, and the present water analyses.

This early work on drill cores was done mainly to see whether the sodium/potassium ratios in the rock could be correlated with temperatures or the natural electrical potentials at various depths in the holes, as determined respectively by Banwell (1955) and Studt (unpublished work). It was hoped that the chemical ratios might be used to locate positions where hot water was moving through the rocks, but the correlation between the ratios and the physical determinations was not encouraging.

The rock analyses as set out in Table 1 do, however, confirm the work of Fenner (1936). Low sodium/potassium ratios are caused both by potassium deposition in the rock and removal of sodium. The fall in the ratio values with depth is not regular, but atomic ratios as low as 0·2–0·5 are often obtained for deep core samples.

The petrology and core analyses indicate that the country is not uniformly penetrated and altered by hot water, but that there are flow zones where alteration has occurred. Series of analyses for increasing depths have not been made for the deeper holes, but a few analyses of cores are available from deeper parts of the more recent production holes. Two analyses are given in the table, including one from a core in the ignimbrite. The chemical changes are similar to those found earlier for shallower depths.

Horstman (1957) found that lithium was concentrated in alteration products such as kaolin and micas. The higher values for the lithium in the cores from Hole 11 indicate that there has been considerable transport of lithium from greater depths. The same effect is shown for Hole 12 but not to so marked a degree. At Hole 12 the sodium/lithium ratio is still above the average value of 28 obtained for Wairakei chloride water, but at Hole 11 the ratio is considerably lower. This is partly due to the loss of sodium.

TABLE 1—Analyses of Drill Hole Cores

Depth (ft)	Type of Rock	*	Oxides Present				Atomic Ratios		
			Na_2O %	K_2O %	Li_2O %	CaO %	Na/K	Na/Li	Na/Ca
			Hole 11						
432	Interbedded mudstone and siltstone	(1)	1·22	2·90	0·032	2·76	0·64	18	8·0
444	Interbedded mudstone and siltstone	(1)	0·58	4·85	0·028	0·96	0·18	10	1·1
460–470	Breccia	(2)	2·30	2·19	0·045	1·56	1·60	25	2·7
650–676	Interbedded siltstone and sandstone	(2)	1·25	5·50	0·056	2·28	0·34	11	1·0
			Hole 12						
126–505	Mudstone and siltstone	(4)	2·11	2·22	0·024	2·42	1·44	42	1·6
700–720	Altered white rhyolite	(2)	1·42	4·30	0·028	1·31	0·50	24	2·0
738	Fresh dark glassy rhyolite	(1)	3·10	1·13	0·018	2·64	4·17	83	2·1
740–855	Altered rhyolite	(6)	3·06	1·45	0·025 (3)	1·79	3·19	59	3·1
1124–1498	Silicified spherulitic rhyolite	(3)	3·33	3·33	......	1·18	1·52	......	5·3
			Hole 20						
1998	Silicified rhyolitic tuff	(1)	1·7	3·6	......	0·4	0·72	......	9·0
			Hole 24						
2729–2738	Altered ignimbrite	(1)	1·2	6·1	0·015	0·65	0·30	39	3·2
			For comparison						
Unaltered Huka spherulitic rhyolite		(3)	3·12	2·40	0·009	1·61	1·98	170	3·5
Unaltered rhyolite, Karangahape, Lake Taupo†		(1)	4·12	2·79	......	2·86	2·24	......	2·6
Unaltered Kaingaroa ignimbrite†		(4)	3·61	3·68	0·005	1·76	1·49	350	3·7

*Number of samples averaged, in brackets. †Steiner (1958), p. 330, except for Li_2O result.

Mr A. Steiner (pers. comm.) has pointed out that under certain conditions there may be considerable rock alteration without any effect on the core analyses, since on decomposition of plagioclase, calcium may be taken up as wairakite, sodium as albite, and potassium as adularia. Both the petrology and core analyses show that increasing calcium contents would be expected in the waters moving near or in the ignimbrite, but towards the surface a decrease could be caused again by deposition of calcium-rich zeolites.

The analyses for calcium in the cores show its solution from the deeper rocks. The information on magnesium is not conclusive. As will be seen later the ratio of calcium to magnesium in the waters is similar to that in unaltered rhyolite and ignimbrite. Steiner (1953) showed that magnesium content is high in cores taken in the first few hundred feet of drilling due to an argillaceous zone formed by downward percolating surface waters rather than hydrothermal solutions. A tendency towards high magnesium contents was found also in four deep cores (Hole 18, 2,830 ft, 1·05% MgO; Hole 19, 2,870 ft, 0·80% MgO; Hole 20, 1,520 ft, 0·85% MgO; Hole 24, 2,738 ft, 0·60% MgO). Unaltered rhyolites and ignimbrites in the area do not usually exceed 0·50% MgO. As only a few analyses of deep cores are available this implied transport of magnesium from greater depths into the ignimbrite should be checked. It is possibly significant that water with the highest magnesium content was obtained from Hole 30, one of the most productive deep holes.

The maximum concentration of calcium in solution at any point in the field is limited by the solubility product $(CA^{++})\ (CO_3'') = S$, for calcite in water at the temperature. Calcite has been found deposited at several parts of the area both in the country rock and in the casing of bores, especially at the south-west portion of the production field.

Mineral solubility tests at 2,000 ft in Hole 27 in July 1957, and at 1,944 ft and 1,050 ft in Hole 31 in July 1959, have given additional data on the equilibria of the various metal ions with the country rock. In Hole 27, and at the base of Hole 31, calcite was not dissolved by the geothermal waters, which must carry almost the saturation amount of calcium in solution for the temperature and carbon dioxide concentration. At 1,050 ft in Hole 31 the waters are under-saturated with calcite.

In all three solubility tests orthoclase ($KAlSi_3O_8$) crystals were not dissolved by the bore waters, which confirms the stable deposition of potassium as this mineral. Albite ($NaAlSi_3O_8$) was dissolved slightly at the base of Hole 31, but a slight growth of the crystals was observed at 1,050 ft.

EXPERIMENTAL PROCEDURE

As the discharge of the drill holes is fed from an underground water-phase at a temperature of about 255°C, the most desirable way of expressing chemical concentrations would be as the ion concentrations in this underground water, which should be the same as the concentration calculated on the whole discharge. It is necessary, owing to the very large difference in the volumes of steam and water in the discharge, to sample water and steam separately. In order to calculate concentrations in the underground water, from the composition of the water sampled, it is necessary to know the enthalpy of the discharge. This is determined more or less regularly by the Ministry of Works, and the average values are sufficiently well known for engineering purposes. Nevertheless, the enthalpy figures for discharges at the actual times of sampling are often not sufficiently accurate or reliable to use in the calculation of concentrations in the underground chloride water. There is also the further difficulty that in a few cases, the enthalpies of the discharges from the holes are so high, that there must be steam present in excess of that which would be given by adiabatic expansion of liquid water at approximately 255°C to atmospheric pressure. In these cases the concentration calculated on the total discharge has no significance, and to obtain the composition of the underground water, it would be necessary to know both the enthalpy of the discharge and the temperature of the underground water. The temperatures at various localities and depths are now fairly well known, but these cannot be relied on for this particular purpose, as the depth at which the main flow into the bore occurs may not be known.

For these reasons, the best basis for reporting the concentrations is the rather arbitrary one of the concentration in the waters separating from the discharges at the boiling point for the local atmospheric pressure, i.e., at approximately 99°C.

In the first stages of the chemical sampling, the bores were discharging from vertical or horizontal pipes, and later the bores discharged through silencers at the ends of horizontal by-pass pipes. (Fisher, 1955, p. 95.) The only way of sampling the water separating at atmospheric pressure was to collect with a bucket some of the water scattered from the main flow at the end of the pipe, or slugs of water ejected from the silencer. This water, after separation at 99°C, was found on collection to be as cool as 70°C, and it was necessary to apply a correction on the assumption that the cooling was due to evaporation in the air. Unless an insulated double-walled bucket is used, the corrected concentrations can be uncertain by 1–3%. Hence this method was used only for quick sampling, when there was not time to get a complete sample.

As, in general, complete samples of the discharge were required, samples of both steam and water were obtained by means of a small separator connected to a valve on the by-pass. This separator discharged steam and water at atmospheric pressure. The sample of water obtained was of the correct composition only if water and steam were drawn into the separator in the proportions in which they were actually present in the discharge at the sampling point. In the early work, at low sampling pressures, the error due to steam and water not being sampled in the correct proportions was neglected. In the later work, the proportion of steam to water in the sample drawn into the separator was measured, and from the enthalpy of the drill hole discharge, a factor was calculated to correct the ion concentrations in the water sample. This factor was generally not much different from 1.000, so that the enthalpy did not have to be accurately known. Until the twin-tower silencers (see below) became available, this method gave the best values for concentrations in water separated at atmospheric pressure.

A few samples were taken while the Ministry of Works were doing large-scale high-pressure separating tests on bores. It was found that the separated water could not be tapped under pressure from a pipe, as the sample was diluted by condensed excess steam from water boiling in the pipe at the sampling point. In this case the water was taken from the open weir box into which the pipe discharged. A small correction to the ion concentrations in this water was required due to the steam being separated from the discharge in two stages: at the separating pressure and at atmospheric pressure.

The present general method for completely sampling the discharge is to pass a sample at known pressure from a valve on the by-pass pipe through a small Webre separator (Pollak and Work, 1942). The separated water passes under pressure through a water-cooled pipe and is collected cold. A knowledge of the enthalpy is required to calculate the ion concentrations in the water separated at atmospheric pressure. Information on the enthalpy of bore discharges is available from the Ministry of Works in the form of graphs of enthalpy against well-head pressure. The enthalpy can then be obtained if the well-head pressure is noted at the time of sampling. The correction is not sensitive to small errors in enthalpy except for discharges of high steam content. It has been found that if the pressure is low (under about 100 p.s.i.) and the valve so situated on the pipe that the sample of the discharge is high in steam, the water sample may be diluted with condensed steam. The most reliable sample is that taken at high pressure (100–250 p.s.i.g.) and although the correction to obtain the concentration on water separated at atmospheric pressure is higher, the possible error in this correction is low.

Most of the bores have now been provided with twin-tower cyclone silencers as described by Smith (1958). Samples of water from the weir boxes of these silencers can be bottled at 98°C, so that the concentrations found by analysis do not have to be corrected appreciably for evaporation. These silencers are found to give good separation of water at atmospheric pressure, and the samples obtainable from them are the best available. It is not possible to get a complete sample of the discharge by sampling steam at the same time, but much useful information on the bores has been obtained by sampling the water only.

There is the question of whether the concrete of the twin-tower silencers reacts appreciably with the waters to alter their calcium and magnesium concentrations. Sufficient work has been done to show that there is a slight interaction with new silencers, but the effect is not important after they have been in use for a few months.

Occasionally, when no other samples could be obtained, waters bleeding from an almost closed pipe were analysed. This type of sample is not favoured, as the small throughput of water allows an unusually high interaction with the country rock, and pipe assembly.

Analysis: Lithium, sodium and potassium were determined in both rocks and waters by flame spectrophotometry. In the comparison method used, a set of synthetic standards were made up to correspond very closely to the overall composition of the samples and to contain known variations of the element under examination.

Rubidium and caesium were also determined by flame spectrophotometry, but the technique was slightly different. Sodium and potassium increase the intensity of the rubidium and caesium emission given by flame excitation. At high concentrations of sodium and potassium this effect tends to become constant. The sodium interference can be neglected if standards and samples are made to contain approximately 5,000 p.p.m. of sodium ions. The potassium interference cannot be overcome by the use of a large excess of this element, due to the proximity of the potassium line at 7665Å to the rubidium line at 7800Å. Instead, the potassium contents of the samples and standards were adjusted accurately to 250 p.p.m. An additional amplifier and a recorder were used with the standard Beckman flame spectrophotometer to enable both greater sensitivity and repeated slow scanning of the rubidium and caesium emission lines.

Calcium and magnesium in the waters were determined by titration with a standard solution of ethylene diamine tetra-acetate. A titration at pH 13 using Cal-Red as indicator gave the calcium concentration, while a further titration at pH 10 in the presence of the indicator Solochrome Black gave the total of calcium and magnesium. The magnesium was therefore determined by difference. Calcium in rock samples was obtained from flame spectrophotometric measurements which were checked for accuracy by a titration method on a selection of samples.

It is difficult to give definite limits of error for the various ion concentrations as the determinations were made on two types of flame spectrophotometers, and by various operators. Approximate limits for lithium, sodium and potassium would be ± 2% for average bore waters. Rubidium and caesium should be accurate to ± 0·2 p.p.m., while the calcium and magnesium values are approximately ± 1 p.p.m.

RESULTS

Table 2 gives the analytical data and the conditions of collection for the waters. The abbreviations used in the table for the various types of sample are as follows:

EHS—From the end of a horizontal silencer;
TT—From the weir box of a twin-tower cyclone silencer;
BP—From a bleeding pipe;
H35—Sample taken from a by-pass at 35 p.s.i.g. through a high pressure Webre separator, the number after H referring in each case to the sampling pressure;
H*35—Sampled from a point on the by-pass but an atmospheric pressure separator used; the concentrations are corrected for a small error caused if the steam and water were sampled in incorrect proportions from the pipe;
H+—As for H* but no pressure recorded, and no correction for incorrect sampling proportions;
S70—Sampled during large-scale separation test at 70 p.s.i.g. by M.O.W., from separated water flashed to atmospheric pressure.

Where the results are available, water analyses are given for each drill hole at approximately yearly intervals to enable any changes in chemical relationships with time to be seen. For the more recent holes the variations are not significant between samples taken in the short time these drillholes have been discharging. The absence of short term variations has been shown on several bores by taking samples at intervals ranging from several minutes upwards.

TABLE 2

Hole No.	Sample Type	W.H.P. (psig)	Date of Sample	Lithium Li+	Sodium Na+	Potassium K+	Rubidium Rb+	Caesium Cs+	Calcium Ca++	Magnesium Mg++	Atomic Ratios			
											Na/K	Na/Rb	Li/Ca	Na/Li
1	H+	..	20/6/50	12·1	1085	78	..	..	..	..	23·8	..	..	27·1
1	H+	..	9/5/52	12·5	1095	73	..	..	56*	..	25·5	..	1·3*	26·4
1	H*46	55	3/11/55	10·4	1000	59	..	..	51*	..	29	..	1·2*	29·0
1	EHS	10	9/1/57	12·5	1170	67	..	..	32*	..	30	..	2·2*	28·2
2a	BP	..	21/9/50	2·1	405	42	..	..	..	..	16·5	..	..	58
2a	BP	..	30/7/53	1·8	350	54	..	..	5·2*	..	11·1	..	2·0*	59
2a	EHS	..	4/9/58	1·8	350	26	..	..	..	..	23	..	..	59
4	H+	90	3/11/50	9·5	900	109	..	..	..	..	14·0	..	..	28·6
4	EHS	..	24/7/51	11·8	1190	143	..	..	..	..	14·2	..	..	30·5
4	H+	59	6/12/52	12·2	1130	146	..	..	26*	..	13·2	..	2·7*	28·0
4	H*48	59	27/6/55	12·3	1280	152	1·7	2·0	..	..	14·3	2800	..	31·4
4	H30	..	3/8/56	9·2	1525	118	..	..	..	..	22	..	..	50
4	H35	45	8/1/57	..	1440	113	..	..	30*	..	22	..	1·8*	..
4/1	H+	..	11/4/51	9·6	1035	67	..	..	55*	..	6	..	1·0*	32·5
4/1	S−	..	6/5/52	6·7	1095	75	..	..	44*	..	25	..	0·88*	49
4/1	H*100	128	24/6/55	13·0	1220	191	..	..	..	..	11·9	..	..	28·3
4/1	H110	..	3/8/56	12·4	1170	184	..	..	..	..	10·8	..	..	28·5
4/1	TT	145	21/10/58	13·4	1220	200	..	..	..	..	10·4	..	..	27·4
4/1	TT	200	23/5/59	13·6	1300	192	2·9	2·0	19·0	2·2	11·5	1700	4·1	28·8
4/2	H+	80	2/5/52	13·5	1185	161	..	..	28*	..	12·5	..	2·8*	26·5
4/2	S−	100	30/7/53	14·1	1320	176	..	..	16*	..	12·8	..	5·1*	28·2
4/2	H*155	195	25/6/55	12·8	1220	184	..	..	..	..	11·3	..	..	28·8
4/2	H*175	..	18/10/56	12·9	1150	184	..	..	..	..	10·6	..	..	26·9
8a	H+	..	11/9/51	2·2	440	56	..	..	..	..	13·4	..	..	60
8a	H+	76	7/2/53	9·3	900	67	..	..	43*	..	23	..	1·2*	29·2
8a	H*62	62	12/9/55	8·6	910	62	..	..	..	..	25	..	..	31·9
8a	EHS	81	30/7/57	7·6	850	63	..	..	..	..	23	..	..	33·7
8	EHS	30	23/5/59	8·3	890	60	..	..	..	..	25	..	..	32·3
9	H+	..	21/7/51	2·8	820	57	..	..	..	..	24	..	..	88

9	S 85	85	1/5/52	4·0	870	64	..	..	5*	..	23	..	4·6*	66
9	S140	140	25/2/54	4·3	910	66	..	..	24*	..	23	..	1·0*	64
9	H*58	100	14/6/55	5·6	1165	78	..	..	..	..	25	..	..	63
9	H 98	98	9/1/57	..	1210	76	..	..	22*	..	27	..	..	..
10	H+	..	12/9/51	5·7	1100	74	..	..	..	..	25	..	..	58
10	H+	29	21/7/52	8·8	1200	99	..	..	42*	..	21	..	1·2*	41
10	H+	39	25/1/54	9·7	1250	90	..	..	40*	..	24	..	1·4*	39
11	H+	..	25/7/51	12·3	1000	103	..	..	..	..	16·5	..	..	24·5
11	H+	72	21/7/52	14·9	1190	144	..	..	29*	..	14·1	..	3·0*	24·1
11	H*61	79	1/11/55	12·5	1260	155	..	..	31*	..	13·8	..	2·3*	30·4
11	EHS	30	29/6/59	..	1235	158	..	..	28	2·5	13·3	..	..	..
12	H+	70	9/12/52	9·2	1080	57	..	..	17*	..	32	..	3·1*	35·4
12	H*67	68	13/12/55	8·6	1110	54	1·1	2·4	49*	..	35	3700	1·0*	38·6
13	H+	63	8/12/52	11·1	1220	61	..	..	45*	..	34	..	..	33·2
13	H*57	61	2/11/55	10·3	1186	52	1·1	2·3	48*	..	39	4000	1·2*	34·7
13	EHS	50	6/10/58	11·6	1260	145	..	..	..	..	14·8	..	..	32·3
14	EHS	..	10/9/52	0·6	685	39	0·5	0·7	43*	..	30	5000	0·08*	340
14	H*45	55	14/9/55	12·0	1180	120	..	..	29*	..	16·7	..	2·4*	29·6
14	H13	30	8/1/57	..	1140	104	..	..	23*	..	18·6	..	..	..
14	H88	93	20/2/58	..	1270	112	..	..	30*	..	19·3	..	2·1*	33·5
15	H+	65	10/9/52	14·6	1200	115	..	..	28*	..	17·8	..	3·0	24·8
15	H*64	80	21/6/55	13·2	1220	128	..	..	..	..	16·2	..	3·1	27·8
15	H63	75	8/1/57	..	1350	140	..	..	25*	..	16·4	..	..	..
16	H+	..	3/12/54	13·1	1040	112	..	..	35*	..	15·8	..	2·2*	24·0
16	H*58	76	15/12/55	10·4	1010	103	..	..	..	..	16·7	..	..	29·3
16/1	H+	41	3/12/54	13·7	1110	118	..	..	34*	..	16·0	..	2·3*	24·4
16/1	H*37	45	15/12/55	11·6	1160	118	..	..	..	..	16·7	..	..	30·1
18	EHS	50	5/7/55	13·1	1220	196	..	..	25*	..	10·6	..	3·0*	28·1
18	H62	73	30/8/56	12·7	1240	188	..	..	..	..	11·2	..	..	29·4
18	H*59	90	27/2/58	..	1310	217	..	..	12*	..	10·3	..	..	..
18	TT	70	23/5/59	14·0	1300	204	2·6	2·0	21	2·3	10·8	1850	3·9	28·0
19	EHS	30	4/12/58	15·6	1340	170	2·8	2·3	..	..	13·4	1800	..	25·9
20	H+	178	28/1/54	16·4	1320	244	..	..	14*	..	9·2	..	6·8	24·2*
20	EHS	127	5/7/55	12·7	1100	197	3·0	2·8	11·7*	..	9·5	1350	6·3*	26·1
20	H3	173	6/8/56	15·1	1320	228	..	..	..	..	9·8	..	..	26·4
20	EHS	180	16/4/57	..	1300	240	..	..	..	..	9·2	..	..	..

TABLE 2—*continued*

Hole No.	Sample Type	W.H.P. (psig)	Date of Sample	Lithium Li+	Sodium Na+	Potassium K+	Rubidium Rb+	Caesium Cs+	Calcium Ca++	Magnesium Mg++	Atomic Ratios Na/K	Na/Rb	Li/Ca	Na/Li
20	TT	200	5/8/58	16·0	1320	230	..	..	..	..	9·8	..	..	24·9
20	TT	200	23/5/59	14·4	1300	227	3·1	2·6	10·1	2·8	9·7	1550	8·2	27·2
21	H*66	95	14/12/55	12·7	1175	138	..	..	..	..	14·5	..	3·0*	27·9
21	H60	93	8/1/57	..	1240	141	..	..	26*	..	15·0	..	..	..
21	EHS	95	13/8/58	15·1	1300	129	..	..	..	..	17·1	..	..	26·0
22	H140	300	31/8/57	12·5	1090	201	..	..	..	..	9·2	..	..	26·3
22	TT	95	12/8/58	12·5	1320	240	..	..	..	..	9·3	..	..	31·8
22	TT	200	23/5/59	14·8	1300	244	..	..	12·4	2·4	9·1	..	6·9	26·5
23	EHS	20	23/5/59	11·8	1270	134	0·9	1·9	21	2·4	16·1	5200	3·2	32·4
24	H*112	230	10/9/55	14·8	1310	225	..	..	11·6*	..	9·9	..	7·4*	26·7
24	EHS	200	29/8/58	14·9	1290	218	..	..	..	..	10·1	..	..	26·1
24	EHS	200	3/4/59	14·2	1330	231	..	..	..	..	9·8	..	..	28·2
25	EHS	35	30/7/57	15·8	1320	220	..	..	..	..	10·2	..	..	25·2
25	EHS	25	14/4/58	..	1350	220	..	..	..	..	10·4	..	..	..
25	EHS	25	3/4/59	14·5	1300	222	..	..	..	..	10·0	..	..	27·0
26	EHS	254	5/7/55	13·7	1250	212	..	..	11·4*	..	10·0	..	7·0*	27·5
26	EHS	235	9/5/57	..	1290	242	..	..	..	..	9·1	..	..	..
26	EHS	243	16/7/58	..	1260	234	..	..	..	..	9·2	..	..	..
26	EHS	200	23/5/59	15·1	1270	236	3·1	2·9	8·8	4·0	9·2	1550	9·9	25·4
27	H108	227	4/8/56	13·7	1210	215	..	..	..	..	9·6	..	..	26·6
27	TT	175	6/8/58	15·9	1330	234	..	..	..	..	9·7	..	..	25·2
27	TT	200	23/5/59	14·8	1300	227	3·3	2·9	10·8	2·0	9·7	1450	7·9	26·5
28	H93	180	6/8/56	14·4	1260	230	..	..	..	..	9·3	..	..	26·4
28	EHS	201	30/7/57	15·5	1260	222	..	..	..	..	9·7	..	..	24·5
28	H46	170	3/6/58	...	1180	211	..	..	20	..	9·5	..	..	..
28	H43	130	7/7/58	..	1180	188	..	..	10·8	..	10·7	..	..	..
28	EHS	200	23/5/59	13·8	1270	226	2·8	2·6	15·0	2·5	9·6	1650	5·3	27·8
29	EHS	56	30/7/57	15·2	1240	206	..	..	..	..	10·2	..	..	24·6
30	EHS	200	30/7/57	15·1	1260	222	..	..	..	..	9·6	..	..	25·2

30	H53	180	17/4/58	..	1205	223	..	..	8·4*	..	9·2	..	..	..
30	H76	220	18/2/59	15·1	1260	198	..	..	1·8	8·1	10·8	..	48	25·2
31	H24	85	22/3/58	..	1300	132	..	..	19*	..	16·7	..	..	..
31	H135	175	12/6/59	13·7	1280	206	2·3	2·6	21·2	6·1	10·6	2070	3·7	28·2
37	H*195	200	7/8/56	12·0	1120	140	..	..	..	..	13·0	..	..	28·1
37	H25	130	10/6/58	..	1280	144	..	..	18·6*	..	15·1	..	..	..
37	H92	114	3/3/59	13·7	1260	147	..	..	25·2	..	14·6	..	3·1	27·8
38	H180	179	3/8/56	11·7	1210	175	..	..	..	..	11·8	..	..	31·2
38	TT	200	22/10/58	13·6	1280	165	..	..	..	..	13·2	..	..	28·4
38	TT	200	23/5/59	13·2	1320	175	..	..	29·6	2·2	12·8	..	2·6	30·2
39	H215	275	2/8/56	12·5	1190	190	..	..	..	..	10·6	..	..	28·7
39	EHS	168	30/7/57	14·0	1250	195	..	..	..	..	10·9	..	..	27·0
39	TT	161	29/8/58	12·3	1300	178	..	..	..	..	12·4	..	..	31·9
40	H163	182	1/10/56	12·2	1050	143	..	..	..	..	12·4	..	..	25·9
40	TT	200	10/11/58	13·2	1230	160	..	..	..	..	13·1	..	..	28·1
40	TT	200	23/5/59	13·2	1300	170	2·5	1·9	24·2	2·1	13·0	1950	3·2	29·7
41	H168	180	20/6/58	..	1170	188	..	..	18·3*	..	10·6	..	..	..
41	TT	200	23/5/59	13·6	1300	194	2·7	2·4	17·5	2·3	11·4	1800	4·5	28·8
42	TT	176	29/8/58	12·3	1300	171	..	..	..	..	12·9	..	..	31·9
42	TT	120	23/5/59	13·6	1300	180	..	..	21·4	2·7	12·3	..	3·7	28·8
43	H96	192	4/8/56	12·6	1180	181	..	..	..	..	11·1	..	..	28·2
43	H48	240	24/6/58	..	1340	180	..	..	18·5	..	12·7	..	..	..
43	TT	200	23/5/59	13·2	1320	186	2·9	2·8	20·6	3·5	12·1	1700	3·7	30·1
44	EHS	170	30/7/57	15·4	1290	221	..	..	..	..	9·9	..	..	25·2
44	TT	200	23/5/59	15·6	1350	238	2·8	2·5	12·1	1·3	9·6	1800	7·4	26·1
45	EHS	54	30/5/57	14·8	1300	174	..	..	..	..	12·7	..	..	26·5
45	TT	65	5/8/58	13·7	1290	157	..	..	..	..	14·0	..	..	28·4
45	TT	50	23/5/59	14·0	1300	172	..	..	26·6	4·1	12·9	..	3·0	28·0
46	TT	200	23/5/59	14·8	1300	238	3·2	2·2	12·9	1·9	9·3	1500	6·6	26·5
47	H102	145	3/2/59	12·8	1230	187	..	..	9·3	4·0	11·2	..	7·9	29·0
48	TT	210	29/6/59	15·4	1335	245	3·0	2·5	10·0	4·0	9·3	1650	8·9	26·2
49	TT	190	6/8/58	15·9	1310	233	..	..	..	..	9·6	..	..	..
49	TT	200	29/6/59	14·4	1235	215	2·9	2·4	11·2	3·9	9·8	1600	7·4	25·8
51	TT	70	23/5/59	14·0	1200	190	..	..	22·6	2·3	10·7	..	3·6	25·8
53	EHS	75	23/5/59	13·3	1270	163	2·2	1·9	25·9	2·5	13·3	2100	3·0	28·8
55	TT	200	23/5/59	14·2	1300	238	2·8	2·4	13·0	1·2	9·3	1750	6·3	27·6

TABLE 2—*continued*

Hole No.	Sample Type	W.H.P. (psig)	Date of Sample	Lithium Li+	Sodium Na+	Potassium K+	Rubidium Rb+	Caesium Cs+	Calcium Ca++	Magnesium Mg++	Atomic Ratios Na/K	Na/Rb	Li/Ca	Na/Li
57	TT	..	5/8/59	..	1140	203	2·7	2·4	..	..	9·5	1550	..	..
58	EHS	180	12/8/58	12·7	1290	200	..	..	..	..	11·0	..	..	30·6
58	TT	200	23/5/59	14·0	1260	195	2·9	2·4	14·9	2·3	11·0	1650	5·5	27·8
67	TT	250	6/6/59	14·6	1310	245	3·2	2·3	12·5	3·0	9·1	1500	6·7	27·1
81	TT	230	6/6/59	14·6	1340	245	..	..	14·9	3·4	9·3	..	5·7	27·6
203	EHS	73	30/7/57	11·7	1170	163	..	..	..	..	12·2	..	..	30·2
203	H14	196	15/8/58	12·9	1320	106	..	..	25·0*	..	21	..	3·0	30·8*
203	H21	275	15/1/59	12·8	1250	131	2·0	2·2	23·2	3·0	16·2	2300	3·2	29·4
211	H21	25	28/10/58	11·7	1270	101	..	..	29·7	7·3	21	..	2·3	32·7
Geyser Valley Springs														
Champagne Pool			11/11/58	10·6	980	75	1·1	2·7	29·5	1·4	22	3300	2·1	27·9
Rainbow Pool			11/11/58	5·8	570	40	..	..	16·8	1·2	24	..	2·0	29·6
Dancing Rock Pool			11/11/58	11·6	1030	70	..	..	31·9	0·8	25	..	2·1	26·8

*Calcium + magnesium.

All the concentrations are calculated as parts per million parts of water by weight for water separated from the drillhole discharges at atmospheric pressure.

Discussion of Results

Chemical Character of the Waters

In discussing chemical analyses of thermal waters it is convenient to use the atomic or molecular ratios between constituents, to avoid the effects of evaporation or dilution with surface waters. The atomic ratios for three sets of constituents are examined in detail – those for Na/K, Li/Ca and Na/Rb. The changes in the first and last ratios with position in the field are caused essentially by variations in the potassium and rubidium concentrations, while in the second ratio changes are due mainly to variations in calcium, but are magnified by smaller changes in the lithium ion concentrations. Sodium ions are the predominant cations in the waters and interaction with the country rocks within the levels of observation cause only small variations in their concentration. The variations in magnesium and caesium concentrations are small and are not expressed as ratios. Because of the large size of the caesium ion – radius, 1·67Å – it does not usually enter positions in mineral structures which are normally occupied by a sodium (0·97Å), calcium (0·99Å), or a potassium (1·33Å) ion.

Rubidium with an ionic radius of 1·47Å is rather similar to potassium in its behaviour and was found by Horstman (1957) to be related to potassium in an almost constant atomic proportion of 1 : 600 in many different types of rock. The rather lower average ratio of 170 in the Wairakei waters may be due to rubidium being concentrated with respect to potassium in an originating high pressure magmatic steam phase. At low temperatures rubidium is taken into the mineral structures at Wairakei more readily than potassium, as evidenced by the rather wider variation in Na/Rb ratios.

The alkali compositions of the waters in the Wairakei field are all of a similar character. It is important to decide whether one, or several different waters feed into the Wairakei system. Table 3 shows ratios of anion constituents which react only slightly with the containing rocks. The samples cover most of the Wairakei area.

Table 3—Ratios of Anion Constituents in Waters in Wairakei Field

Sample	Atomic Ratios			
	Cl/F	Cl/B	Cl/As	Cl/Br
Hole 11	140	23.0	1000	......
Hole 13	170	23.8	920	800
Hole 30	165	24.9	1050	860
Hole 37	163	23.9	1020	870
Hole 43	164	24.5	1050	850
Champagne Pool	160	23.8	1030	1000

To examine further any variations in anion relationships the drillholes were divided into two groups: (A) holes, mainly in the Western area, which draw on waters in or about the ignimbrite sheet; (B) holes drawing water from permeable volcanic breccias. These are mainly in the East where the ignimbrite is downfaulted to a depth greater than that reached by the drillholes.

The mean values of chemical ratios for each hole have been combined to give weighted mean ratios for the two groups. Weighting was given first according to the number of results from each hole. If each hole samples a body of underground chloride water with uniform anion relationships, its output should have little effect on the values obtained. However, in practice the holes of higher output do give more reliable samples, so that a simple weighting of 2 was given for the general run of holes, 3 for holes of very high output, and 1 for holes of poor output.

The similar values for anion constituent ratios as shown in Table 4 show that the holes in the Wairakei area are all fed with water from the one source.

Weighted mean ratios have also been calculated for the alkali metal ions and Table 5 gives a comparison between the two groups of holes. Use of the same method of weighting is clearly questionable but the table is intended only to show the general trend in alkali compositions as the chloride waters move upwards and away from the ignimbrite sheet.

TABLE 4—Weighted Mean Values of Constituent Atomic Ratios with Standard Deviations

—	Ratio		
	Cl/F	Cl/B	Cl/As
Group A	165 ± 4	24·0 ± 0·2	995 ± 40
Group B	162 ± 3	24·2 ± 0·2	965 ± 40

TABLE 5—Weighted Mean Values of Constituent Atomic Ratios with Standard Deviations

—	Sodium m mole/l	Atomic Ratios				Calcium m mole/l	Ca/Mg	Li/Ca
		Na/K	Na/Li	Na/Ca	Na/Mg			
Group A	57·1 ±0·2	9·8 ±0·2	27·0 ±0·1	180 ±10	520 ±25	0·62 ±0·04	2·9 ±0·1	6·7 ±0·4
Group B	55·8 ±0·3	12·7 ±0·4	29·1 ±0·6	117 ±7	520 ±20	0·98 ±0·04	4·5 ±0·2	4·0 ±0·2

Variation of Constituent Ratios with Position

In the discussion which follows it is assumed that water of a common origin enters into the system through faults or fissures in the ignimbrite sheet. Further, it is suggested that these waters may not have had any great interaction with the walls of the ignimbrite, as the fissures which have so far been located by drilling are well lined with silica. The waters entering the Wairakei breccia aquifer may have very similar alkali compositions at the points where they leave the ignimbrite at depth.

The effect of lateral movement of water beneath the ignimbrite sheet cannot be studied, but if there is a large volume breccia aquifer beneath the ignimbrite, it is probable that the alkali composition of the reservoir water will be constant throughout, and approximately in equilibrium with the containing rock.

The variations in the ratios Na K, Na Rb, and Li Ca with the positions of the holes in the field are shown in Figs 1–3 which are maps incorporating the most recent ratios available for each sampling point. These maps are a projection of the results on to a horizontal plane. The depths of the holes must be carried in mind when the patterns given by the maps are examined.

The following shallow drillholes have not been included in the mapped results (total depths in feet from Smith, 1958):

> Hole 1 (600 ft), 2a (1,001 ft), 8a (635 ft), 9 (563 ft), 11 (886 ft), 14 (569 ft), 15 (829 ft), 16 (993 ft), 16/1 (994 ft) and 17 (989 ft).

In addition, the Hole 23 results are not mapped as this hole is only cased to 489 ft. The remaining holes are cased to levels ranging from about 800 to 2,000 ft, the total depths being usually several hundred feet greater. East of Hole 45 the bores are cased to approximately 1,000 ft depth, as are Holes 203, 31, 24, and 29. The remaining Western holes are drilled usually to about 2,000 ft and produce from beneath casing depths of 1,200–2,000 ft.

The concentrations of the alkali ions change as the water travels through the breccias in both vertical and horizontal directions. This is shown by the results for Holes 11 and 47, which are close together, but are cased to 720 and 2,067 ft respectively. The ratio Na/K for Hole 11 is 13·3, and for Hole 47 is 9·1. The change in ratios with position can be seen clearly for the Eastern group of holes which are all cased to similar depths but have Na/K ratios ranging from 11·0 to 13·7. As the hot waters may at times move along large and perhaps silicified channels there may be only small changes in ratios in some cases for water movement of a given distance, while in others, where percolation through smaller channels occurs the changes in ratios may be greater.

The alkali ion concentrations in the waters from each hole should be treated as an individual case, taking into account the position, depth of feeding zone, and geological environment. Figs 1–3 give a general picture of the flow pattern which exists at the 1,000–2,000 ft level in the system. Because of the uncertainties in the levels at which holes tap water, and in the type of country rock and the minerals the water has contact with on its journey, the information cannot be regarded as precise for prospecting purposes. It does however give many important facts.

It can be assumed that waters in the West with their high potassium and rubidium concentrations have travelled the least distance from the common reservoir or hot water flow. This assumption is supported by the lower concentrations of calcium in the waters from this area. From the Na/K ratios, the areas west between Holes 44 and 46, and west between 47 and 26 seem the most promising siting positions for further holes. However, other factors such as temperatures, faulting, and strata permeability must also be examined in conjunction with the chemical results in order to estimate future drillhole performance.

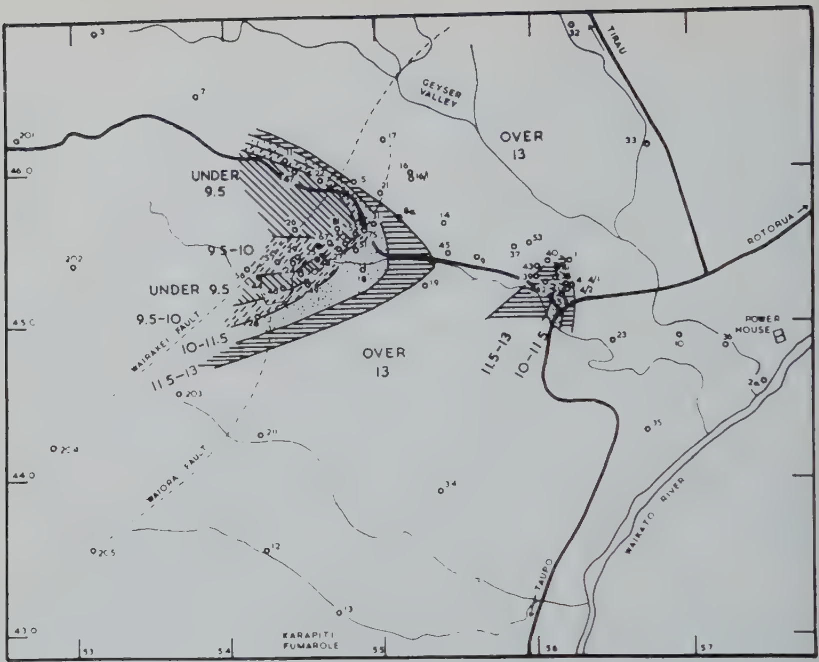

FIG. 1—Sodium/Potassium ratios.

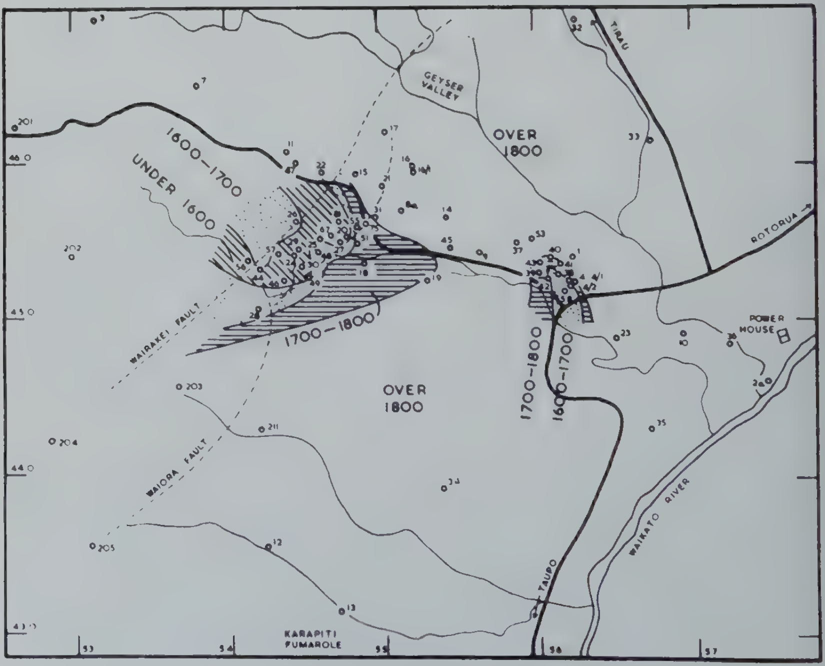

FIG. 2—Sodium/Rubidium ratios.

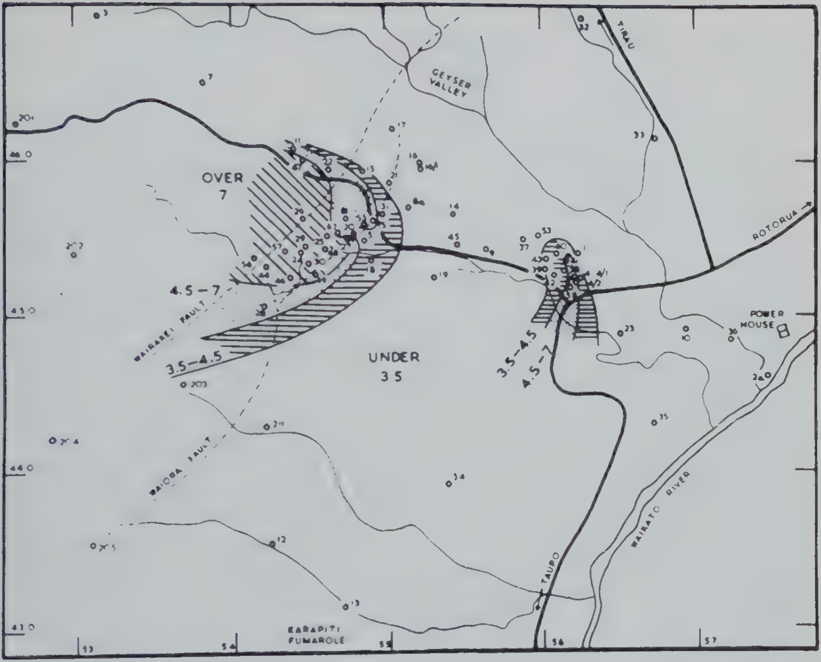

Fig. 3—Lithium/Calcium ratios.

In the Eastern "circle" area the distribution of the ratios suggests that there is a separate feeding channel about this point. The concentrations of potassium, rubidium, and lithium are lower than in the west, while calcium is higher. This may only be the result of a longer time of contact with the breccia beds as the water travels upwards from a fault in the ignimbrite. Hole 37, drilled to 3,340 ft failed to strike the ignimbrite, which is downfaulted to the East (this hole is now partly filled in and has an open hole depth of 1,607 ft). In contrast many of the holes in the West reached the ignimbrite sheet at about 2,000 ft. A cross section of the field was given by Studt (1958).

From the ratios obtained for the holes in the Eastern area it is difficult to see that the ignimbrite sheet is far below 3,340 ft, otherwise the potassium contents of the waters from the eastern holes should be lowered by a much greater extent in the time taken by the water in its long journey to the surface. These holes produce water from levels ranging from about 1,000 to 1,500 ft. Percolation upwards through several thousand feet of breccias would have a more marked effect on the ratios, unless of course a well defined and silicified channel was present through them. Again compare the change in Na/K ratio from 9·1 to 13·3 for adjacent holes 11 and 47 caused by the difference of approximately 1,300 ft in their casing levels.

The present maps may be compared with the Wairakei isotherms at depths given by Banwell (1960) and the thermo-artesian pressure maps of Studt (1958).

There is good agreement in detail with Figs 3, 4, and 7 of Studt's paper, but there is no feature in the chemical distribution that corresponds to the pressure high about Hole 19. This could be explained if the country at this point was very impermeable, leading to small flow rates and high interaction of the waters with the rocks. The low pressure area to the West of Holes 26, 25, 24, 44, also appears on the Na/K map as containing waters low in potassium, compared with the areas immediately North and South.

The isotherm distribution is also matched essentially by the alkali results. Separate temperature highs in the Western and Eastern areas correspond to the areas of low Na/K, Ca/Li, and Na/Rb ratios, both sets of information showing active feeding zones in these vicinities. Several of the holes shown by Banwell to be tapping lower temperature water have high Na/K, Ca/Li and Na/Rb ratios. The cooler water may be partly due to steam separation and partly to convection cycles within the breccias carrying cooler water depleted in K and Rb into certain points. Examples of these lower temperature holes are: Hole 31, 230°c, Na/K = 10·6; Hole 25, 230°c, Na/K = 10·0; Hole 18, 230°c, Na/K = 11·0. A few cases where agreement is not so good are the bores 29, 24, and 51 which are shown by Banwell to be tapping water over 245°c, yet have Na/K ratios of 10·2, 9·8, and 10·7. *Changes with Time:* Many holes, particularly the more shallow ones drilled early in the project, discharged for long periods before fairly stable concentrations of components were attained in the waters. This effect was probably due to the presence of diluted, rather stagnant waters in the breccias when drilling commenced at Wairakei.

This effect was not important for the newer deep production holes which almost immediately after blowing gave waters with chemical concentrations very similar to the older deep holes. There has been very little change in ion concentrations in the waters from the deep holes over a period of several years. The major drillholes and many of the older ones of medium depth now produce waters with almost identical concentrations of unreactive constituents.

A proportion of ground water is carried by convection into the surface feeding zones of some of the shallow holes towards the river in the East, and even the deeper Holes 38–43 with the salt concentration in their waters approximately 4% lower than those from the Western holes, may be affected by this process.

The changes in alkali ion ratios with time are rather as would be expected from the concentration change pattern. The shallow holes tend to be variable. Waters from holes such as 4/1, 4/2, 13, 14, 23, which have increased in ion concentration since the holes were opened, have decreased in Na/K and Ca/Li ratios. Three Holes – 1, 4, and 8a -- have increased their Na/K ratios with time, but the water output of 8a is now very small. The changes for Holes 1 and 4 are slight, and for Hole 4 is probably connected with the unusually high ion concentrations in the waters.

The fall in Na K ratios for Hole 4 1 from 26 in 1951 to 12 in 1955, and for Hole 13 from 34 in 1952 to 15 in 1958 are indications of the general flushing out of the surface breccias by the increased flow to the various holes.

The ratios for the major holes vary much less with time and for many can be regarded as constant in the period of observation. Hole 21 shows a steady increase in Na K ratios from 14·5 in 1955 to 17·1 in 1958 which may show that this boundary of the field is gradually being cut off from the main flow of hot water.

Hole 30, which shows Na K ratios varying by much more than the experimental error, is also remarkable for its low calcium and high magnesium concentration. Rather irregular ratios were also obtained for Holes 203, 19, and 28. The water steam ratio for Hole 203 has also changed in the last two years. This hole now gives a discharge of almost dry steam.

The present picture given by the Na K ratios, and their variation with both time and position of water sampling, is consistent with a continuous flow of hot water through the Wairakei breccia beds. If appreciable recycling of water took place in the porous beds above the ignimbrite the potassium content could be expected to be much lower than that found in the waters from any of the shallow bores.

The small chemical changes with time, both in alkali compositions and relative concentrations of other constituents, provide evidence for a long life for the hydrothermal system. It is probable that the geothermal waters are mainly surface waters that have passed through a very deep flow cycle in which they have been heated and charged with chemicals. If the hold-up volume in the deep "reservoir" beneath the ignimbrite is not large compared with the excess of the present water draw-off over the natural flow for the period, it could be expected that changes in the compositions of the discharges from the deep bores would have occurred through a shift in the dynamic chemical equilibrium below. As will be discussed, all the water constituents cannot be derived simply by a leaching process in the beds under the ignimbrite.

Origin of Chemicals: An important question is that of the origin of the various substances dissolved in the geothermal waters. Two main possibilities exist: (1) leaching the country rock by the hot waters; or (2) the addition of chemicals along with heat from a high temperature and pressure magmatic steam phase. Above the ignimbrite there is definitely a considerable amount of secondary interaction of water with country rock minerals, but the broad chemical character of the water must be derived deep beneath the area by one or both of these mechanisms.

It is considered by Craig, Boato, and White (1956) from isotopic evidence that the content of magmatic steam is very small in geothermal waters, and that they are essentially recycled ground waters which have been heated by conduction at depth. In the conduction mechanism of heating the dissolved substances must be derived by leaching of the country rock.

White (1957) used the lithium contents of many geothermal chloride waters as evidence that most of the dissolved alkali ions were carried from a magma by a high density steam phase. As the lithium concentration of geothermal waters may be 20% of that of the rocks of the area, it is difficult to see how sufficient contact between rock and water could be maintained over long periods to obtain the required transfer to the solution phase by leaching.

The present caesium determinations provide more striking evidence that all the constituents in the water cannot be derived by leaching. Horstman (1957) gave the caesium concentration of igneous rocks of granitic composition as about 1 p.p.m. The caesium concentration of unaltered Wairakei ignimbrite has been found in this laboratory to be less than 0·5 p.p.m. With this confirmation of the low caesium content in the rocks it seems impossible that the amount in the waters could be derived by leaching.

Eugster (1955) determined the distribution of caesium between high temperature steam and sanidine (a high temperature feldspar, essentially $KAlSi_3O_8$), and showed that the ratio (Cs/K sanidine)/(Cs/K steam) is for 1,000 atmospheres about unity at 720°C but drops to about 0·25 at 400°C. At lower temperatures water will concentrate caesium from the rock, but an impossibly large quantity of rock must be leached by each volume of water to obtain the required concentration.

The approximate quantity of rhyolite required to give the yearly output of the various components found in the waters from the natural Wairakei springs is shown in Table 6. Complete transfer of the component from rock to water by leaching is assumed in each case. The outputs are based on the chloride output measurements of Ellis and Wilson (1955).

TABLE 6—Quantity of Rhyolite Required to Give Yearly Output of Components of Waters of Wairakei Springs

Component	Output from Wairakei g/year	Approximate Content in Unaltered Rhyolite (p.p.m.)	Rhyolite Required Per Year (Km^3)
Cl	2×10^{10}	400	0·02
B	1×10^{9}	10	0·04
F	8×10^{7}	50	0·0006
Li	$1·5 \times 10^{8}$	50	0·001
Cs	$2·5 \times 10^{7}$	less than 0·5	greater than 0·02
As	6×10^{7}	3·5	0·01

There is also the possibility that chloride, boron, and other magmatic constituents could come from the leaching of some of the large deposits of volcanic ash and pumice ejecta. One of the authors (Wilson, 1953) considered that ash ejected in a volcanic eruption might absorb constituents from the magmatic steam, and that these would be easily leached out by water. The matter extracted by cold water from a fairly fresh sample of andesite ash from a recent eruption of Ngauruhoe was determined. The ash contained 300 p.p.m. of chloride soluble in water, and 700 p.p.m. of water-insoluble chloride. A similar result has been obtained by Tovarova (1958), who found the content of soluble chloride (Cl^-) from three samples varied from 230 to 960 p.p.m.

Wilson (1953) also found a content of 2,300 p.p.m. of soluble sulphate and 24,600 p.p.m. of water-insoluble sulphate in Ngauruhoe ash, while Tovarova (1958) found contents of soluble sulphate from 1,600 to 4,000 p.p.m. The small amount of sulphate (30 p.p.m.) in Wairakei bore waters could possibly come from leaching of volcanic ejecta.

As it would be impossible to extract all the chloride, boron, etc., from the igneous rocks it appears that the quantity of rock required to give the output of the chemicals in Table 6 for a period of, say, 10^4 years is much too large for any local leaching process to be important.

There is also little evidence that the chloride could be supplied by the local leaching of sedimentary rock. According to Behne (1953), the average chloride content of sedimentary rocks is about the same as the average in eruptive rocks (about 150 p.p.m.).

If the chemical components were derived from the addition of a minor quantity of magmatic steam to deep circulating ground waters the difficulty is removed. Because the distribution of caesium between the water and rock is of the order of unity at 800°C (Eugster, 1955), it is necessary that the rock melt be enriched in caesium over the normal rock concentrations. This is only likely if the major portion of the rock magma chamber has crystallised, leaving an alkali- and volatile-rich magma solution. The minimum total size of the magma chamber is dependent on the lifetime allotted to the area, but a size of at least a few hundred cubic kilometres would be necessary, unless the magma has assimilated quantities of sedimentary or metamorphic rocks rich in the required chemicals. This aspect will be checked by analysis of the various rocks of the thermal area basement and surface strata for the elements in Table 6.

If, to avoid conflict with isotopic evidence (Craig, Boato and White, 1956) the quantity of magmatic steam in the final solution is limited to 10%, approximately two-thirds of the heat contained in the hot chloride water phase at 250°C remains to be accounted for.

As the chloride content of the Wairakei water at 250°C is 0·15%, that of the original magmatic steam would be 1·5% if a one-to-ten dilution is assumed. This concentration is in reasonable agreement with volcanic gas analyses, and would agree also with the hypothesis that the water and chlorides of the ocean have been derived from magmatic gases through geological time. The chloride may not all be juvenile chloride, but some of it may well be derived from sea-water held in sediments. Through melting of the sediments, this chloride could pass again into magmatic gases, and hence again through the geological cycle. This does not affect the above hypothesis, except that the yearly amount of chloride discharged by volcanic action, etc., must be higher to allow both for recycled chloride; and for the increase in oceanic chloride with time.

Various convection models for heat transfer to deep circulating ground water by conduction from cooling magma have been examined by Banwell (1958) and White (1957). There are difficulties in fitting an appropriate conduction and convection model into the physical limitations of the Wairakei system, i.e., the minimum depth and age of magma, the permeability of the covering sediments, and the radius of the area. To obtain sufficient heat transfer it is necessary to assume a convecting magma chamber rather than a cooling sheet.

It is assumed that the heat at Wairakei is derived partly by conduction and partly by magmatic steam as ground waters pass through a deep convection cycle.

It is a plausible hypothesis that the energy to supply the Wairakei hydrothermal system had a similar origin to that of the energy required to erupt the pumice lapilli in one of the Wairakei-Taupo ash showers. Although the steam pressure was not enough to give an eruption, the energy may be of a similar order.

One of the authors (S. H. Wilson, to be published) has calculated the energy required to erupt the pumice lapilli that came from one of the pumice showers in the Wairakei-Taupo region. The data for thicknesses of pumice from this shower, the Waimihia shower, are given by Baumgart (1954). The quantity of ash ejected was neglected, although it was probably of about the same mass as the lapilli, and the efficiency of the steam explosion was arbitrarily taken as 10%. It was found that the amount of steam necessary to cause the Waimihia eruption would supply the natural activity at Wairakei for 15,000 years. This estimate was based on the assumption that $^1/_3$ of the energy comes from magmatic steam and $^2/_3$ from heat by conduction. If the content of steam in the magma is taken as 5%, then the volume of magma required to supply the steam is 140 km^3, or, for example, an intrusive block 7 km × 7 km × 3 km. This is not unreasonable. If the chloride content of the steam is 2%, then the chloride supplied by the magma would have to be 1,000 p.p.m. of its mass. As the average chloride content remaining in igneous rocks on solidification is 150 p.p.m., the total content in the magma would have to be about 1,200 p.p.m.

The concentrations of salts carried by the high pressure magmatic steam will be dependent on its density and hence the depth of the magma intrusion. It is likely that chloride is carried as alkali chlorides rather than hydrochloric acid.

$$H_2O + SiO_2 + 2\,NaCl = Na_2SiO_3 + 2\,HCl$$

For reactions of this type to give an appreciable concentration of HCl in the steam the intrusion would have to be impossibly shallow, e.g., at 800°c for 1 atmosphere of steam over separate silica and NaCl phases the molar ratio $HCl/H_2O = 0{\cdot}01$, and for 1,000 atmospheres of steam $HCl/H_20 = 0{\cdot}0003$.

The constituents such as Cl, F, B, Li, Rb, Cs, found in the Wairakei waters are all substances which tend to concentrate in the more silica- and alkali-rich residual magmas. The calcium and magnesium contents of the waters are low. These facts would support the idea that an intrusion of rhyolite or dacite, rather than andesite or basalt, is the immediate source of the heat and the chemicals.

The original ratio of Na/K in the steam separating from the magma phase will depend on the temperature, the pressure and depth, and the stage of crystallisation. Bowen and Tuttle (1950) studied the system $NaAlSi_3O_8 - KAlSi_3O_8 - H_2O$ and found that, at water pressures of about

1,000–2,000 atmospheres, feldspars crystallise from the melt over most of the composition range as a solid solution series with a minimum melting point around 800°C at 35 mole % $KAlSi_3O_8$. The relative activity of Na^+ and K^+ ions in the melt will change as crystallisation proceeds, but for an average rhyolite composition it probably never deviates from unity by more than a factor of two or three.

This implies that there is beneath the ignimbrite layer a very large volume of reactive (therefore probably permeable) country where considerable quantities of potassium are continually being abstracted from the waters to raise the Na/K ratio from about unity to nine. The quantity of potassium lost at these deep levels may be ten times the amount lost in the surface breccias.

Other Alkaline Earth Metals: The ions Sr^{2+} and Ba^{2+} have been detected in the waters at a concentration of about 0·1 and 0·01 p.p.m. respectively but little work has yet been done on their quantitative estimation. White (1957) reported 0·6 p.p.m. Sr^{2+} in the waters at Steamboat Springs, Nevada. Analyses of many of the drill cores from Wairakei show 0·01–0·15% of strontium and barium in the hydrothermally altered rocks.

Other Hydrothermal Areas: Many analyses exist for lithium, sodium and potassium contents of hydrothermal waters. White (1957) gave a series of analyses from selected areas in the world and many well known monographs and papers exist on the various major geothermal regions.

As a comparison for the Wairakei results the concentrations and atomic ratios of Na^+, K^+, Li^+, Rb^+, and Cs^+ ions are shown in Table 7 for several New Zealand geothermal areas as well as similar published information on some Japanese hot-springs (Yamagata, 1951 A, 1951 B; Kimura, 1949).

TABLE 7 – Concentrations and Atomic Ratios of Alkali Metal Ions in New Zealand and Japanese Hot Springs

Source	Na^+ (p.p.m.)	Atomic Ratios			
		Na/K	Na/Li	10^{-3} Na/Rb	10^{-3} Na/Cs
New Zealand					
Wairakei drillholes	1300	9.5	25	1.6	3.0
Bath's source, Tokaanu	1820	19	23	6.1	2.2
Large Ohaki pool	880	18	30	6.5	4.2
Waipapa geyser, Orakei	390	20	35	2.4	1.6
Champagne pool, Waiotapu	1170	13	41	3.1	3.6
Rachel Spring, Rotorua	540	33	71	2.5	2.6
Te Horo, Whaka	470	12	31	2.9	3.4
Japan					
Shionoha Spring Nara Pref.	.....	......	4*	0.4*	0.3*
Average, Mt Zao hot springs, Tohoku district	......	33	1100	50	330
Average, Kutsatzu Shirane volcano area	......	4.0	500	10	33
Arima hot-springs, Shin Onsen	15614	7.3	89	10	23

*Concentrations of Li, Rb, and Cs in p.p.m.

In the pools it is probable that much of the rubidium and potassium has been removed by reaction near the surface with the containing rocks. Caesium and lithium on the other hand are not so reactive because of their extremes in ion sizes, and as can be seen from the Wairakei examples, are mostly carried to the surface in solution.

Apart from the examples chosen from Rotorua and Ohaki, there are not great differences between the samples as far as Na/Li and Na/Cs ratios are concerned. It would seem that this could come about only if the rock magma from which the heat and chemicals are derived is very similar in composition for each area. The Japanese results show the ratios can vary widely between regions.

The large concentration of caesium at Tokaanu (4·7 p.p.m.) is worthy of note and may be of economic value in future years should a market for this element appear. As the element with the lowest ionisation potential it may be of future importance in the field of ion-powered rockets (Barton, 1957) and high-temperature thermoelectric devices.

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Special thanks are expressed to colleagues for the following aspects of the work: W. A. J. Mahon was responsible for organising the collection and analysis of waters at Wairakei in the last 18 months; alkali analyses for cores from Holes 11 and 12 were provided by H. P. Rothbaum; and the remaining rock analyses quoted were completed for the information of the Geological Survey by J. A. Ritchie; the rubidium and caesium concentrations in the waters and the lithium analyses for some of the rocks are due to R. M. Golding and M. G. Speer.

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RELATION OF KAKANUI SCHIST TO KAIHIKUAN SEDIMENTARY ROCKS AT MT ST MARY, NORTH OTAGO

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(Received for publication, 4 July 1960)

Summary

The sequence at Mt St Mary has been described as uninterrupted with a transition from schist to sedimentary rocks of Kaihikuan age. The schist is shown to be separated from the sedimentary rocks by a fault for which the St Mary Fault is proposed. Consequently the age of the beds metamorphosed to schist may be appreciably older than Kaihikuan.

INTRODUCTION

James Park (1904) discovered fossils in place near the summit of Mt St Mary in 1903. He described an uninterrupted sequence of at least 10,000 ft of beds from Kakanui Schist at the base passing upwards to the fossiliferous sedimentary rocks which he termed the Mount Mary Series (Mount St Mary Series of Park, 1918, p. 13). The fossils collected by Park and his companion Hamilton were referred by Marwick (1953, p. 13) to his Kaihikuan Stage (about Ladinian).

Park's conformable sequence from schist to Kaihikuan sedimentary rocks has been used by many writers as evidence to date the rocks now metamorphosed to schist. (Park, 1908, p. 28; 1918, p. 13; Turner, 1938, p. 161; Mackie, 1936, p. 140; Ongley, 1939, p. 32; Paterson, 1941, p. 38; Amies, 1952, p. 379; Reed, 1958, p. 48). Mackie (1936) agreed with Park that the schist conformably underlay the Kaihikuan sedimentary rocks and that there was a transition from schist to greywacke.

During geological mapping in the Waitaki Valley, the writers discovered a faulted contact between argillite and schist near Aviemore homestead on the main Kurow-Omarama road. The fault was subsequently traced for nine miles to the south-west to Awahokomo Creek immediately to the east of Mt St Mary, where it separates Kakanui Schist from the *Mt St Mary Formation*[1] of Kaihikuan age. It is proposed to name this fault the *St Mary Fault*. It lies to the south-west of the Wharekuri-Otekaieke[2] Fault of Uttley (1920, p. 137). (See Fig. 1.)

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[1] The writers propose the term Mt St Mary Formation for Mt St Mary Series of Park (1918, p. 13) as Series is a time-rock term.

[2] Otakaieke was adopted as the correct spelling by the New Zealand Geographic Board, January 1953.

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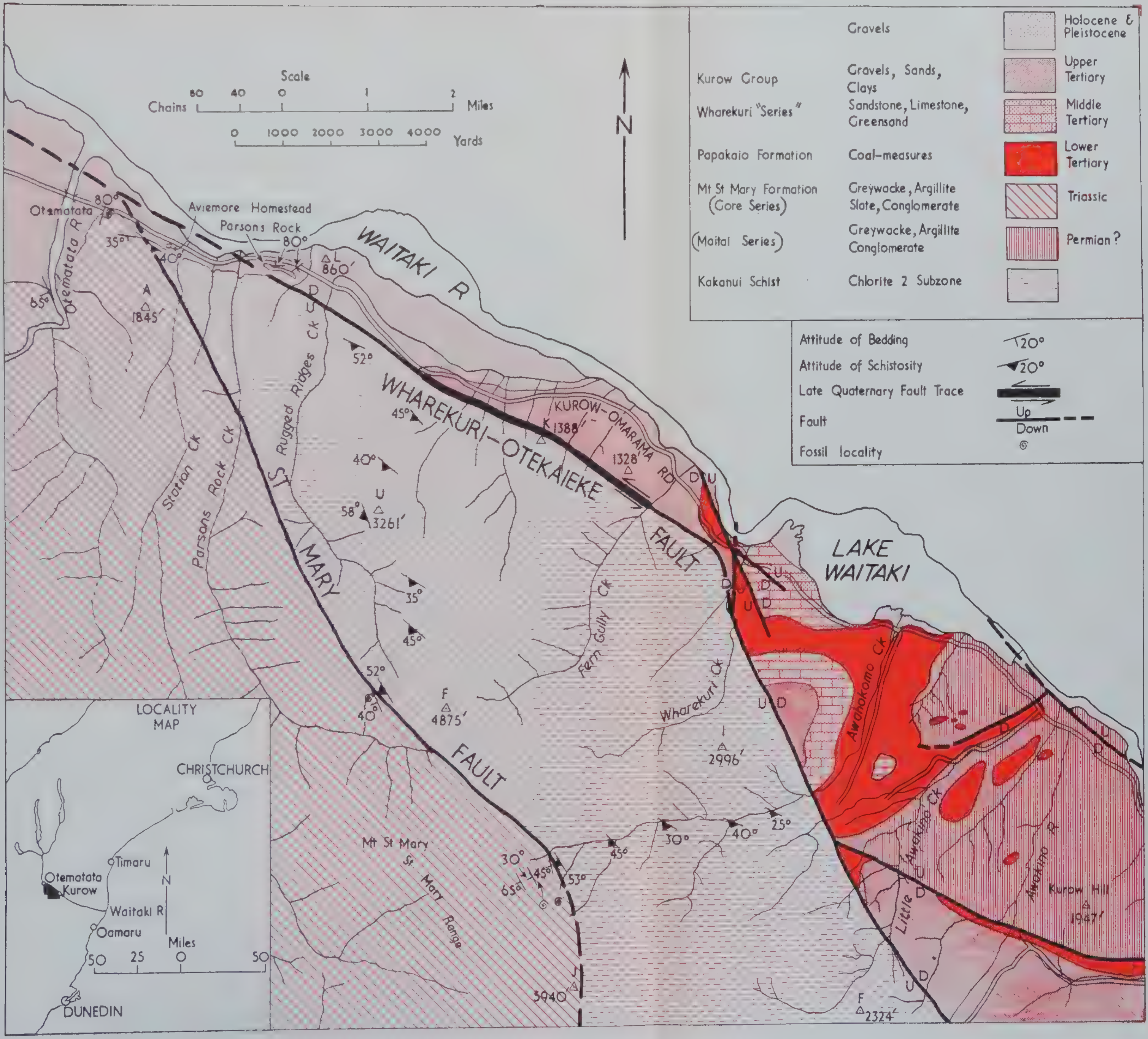

FIG. 1—Geological Map of Otematata - Mt St Mary District, North Otago (Tertiary Geology after Marwick, 1935)

facing p. 618

PRE-TERTIARY ROCKS

The Mt St Mary Formation consists of fine to medium grained greywacke and argillite with subordinate blue-grey slates and quartz pebble conglomerates; quartz veins are scarce. The fossiliferous beds crop out in several places in the headwaters of Awahokomo Creek (see Fig. 2) and those examined by the writers are at least 50 ft thick and consist predominantly of silt-wacke in which most of the fossils occur. The fossils in the few thin greywacke bands are slightly distorted but those in the finer-grained beds are much flattened. The fossils indicate a Kaihikuan (Ladinian) age for the sediments (Marwick, 1953, p. 13). Mr I. G. Speden, N.Z. Geological Survey, who studied the distortion of the fossils which are randomly distributed on apparent bedding plane surfaces on non-oriented blocks in collections at N.Z. Geological Survey, reported (letter 29 April 1959) as follows:

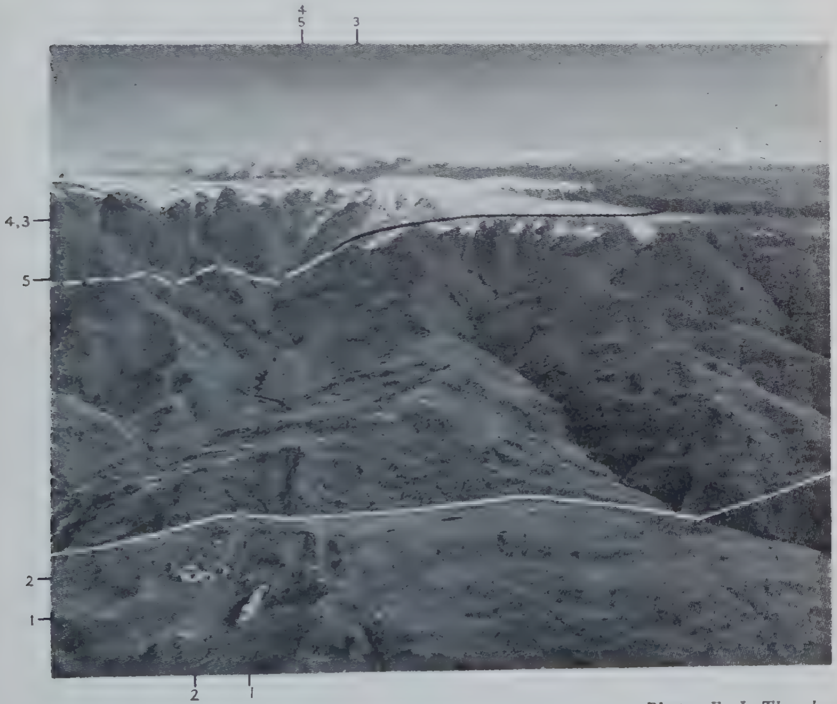

Photo: E. J. Thornley

FIG. 2—Mt St Mary showing Wharekuri-Otekaieke Fault, in foreground, and St Mary Fault in background. Awahokomo Creek is on the left and Wharekuri Creek on the right. The Kaihikuan fossiliferous beds occur in place at 3.3, and 4.4. Tertiary limestone crops out in the foreground at 1.1 and 2.2, Kakanui Schist occurs between the faults, and Mt St Mary Formation beyond the St Mary Fault. An exposure showing argillite and schist in proximity occurs at 5.5. The strikingly flat surface of the St Mary Range shows that it represents the but little modified pre-Tertiary peneplain. Aerial view looking west.

> "The flattening of the spire of specimens of *Naticopsis* ? sp. (see Wilckens, 1927, Pl. 8, Fig. 1) and of an indeterminable gastropod in a direction perpendicular to its length, the flattening of brachiopod valves in directions both parallel and perpendicular to the commissural plane, and the orientation of a spiralium of *Athyris kaihikuana* (Trechmann) to the specimen and to the surface on which the specimen lies (see Wilckens, 1927, Pl. 10, Fig. 1) indicate that compaction has occurred. Frequently, double-valved specimens have the peaks of each valve displaced relative to each other, and the folds, plications and dental apparatus modified in various ways. The inclination of axial planes through the crests of plications and folds, and the inclination of hinge-line structures, have been displaced relative to that of undistorted specimens. On some specimens the inclination on both sides of the plane of symmetry (of brachiopods) is uniform, but in others it is markedly different. Associated with this, the degree of over-curving of the crest of plications on each side of the plane of symmetry may be comparable or divergent. Whereas on some blocks there are up to 3 or 4 specimens showing general uniformity of degree and orientation of distortion, thus simulating stretching, there are always other specimens either relatively undistorted, or with distortion in different orientations. Two blocks have slickensiding on the other non-fossiliferous surface. The relative direction of movement causing the slickensiding is indefinite. On these blocks, both small, the distortion of specimens is random, and on one the distortion of folds and plications on each side of the plane of symmetry of a small specimen of *Spiriferina kaihikuana* is markedly different and also divergent from the axis of movement indicated by the slickensiding. There can be no doubt that the distortion of this specimen is due to compaction only and is unrelated to the stress causing the slickensiding.
>
> In conclusion, the material in our collection provides no evidence that the Mt St Mary fossils are distorted by any mechanism other than compaction."

Samples from this formation submitted to Dr J. J. Reed ([3]P.22164; P22386; P22882, P23517a–c) were placed by him (pers. comm.) in the Chlorite 1 sub-zone and close to the Chlorite 1–2 isograd.[4]

The Kakanui Schist (Kakanui Series of Hector, 1865, p. 128; Kurow Schists of McKay, 1882, map, p. 80) in the area mapped by the writers is a low grade schist, mostly with planar schistosity, which in many places shows distinct foliation (Fig. 3). The writers are using the term foliation with no genetic connotation; the foliated appearance is due to the alternation of light green quartzo-felspathic arenaceous layers from ½ in. to 1 in. thick with darker green finer-textured apparently micaceous layers ⅛ in. to ¼ in. thick. This layering may be due either to metamorphic segregation or to bedding accentuated by metamorphism. Quartz veins up to several inches

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[3] Numbers refer to rocks and thin sections in collections of the New Zealand Geological Survey.

[4] See also description by Dr Reed of matrix of fossils from Mt St Mary in Speden (1960, pp. 515–7).

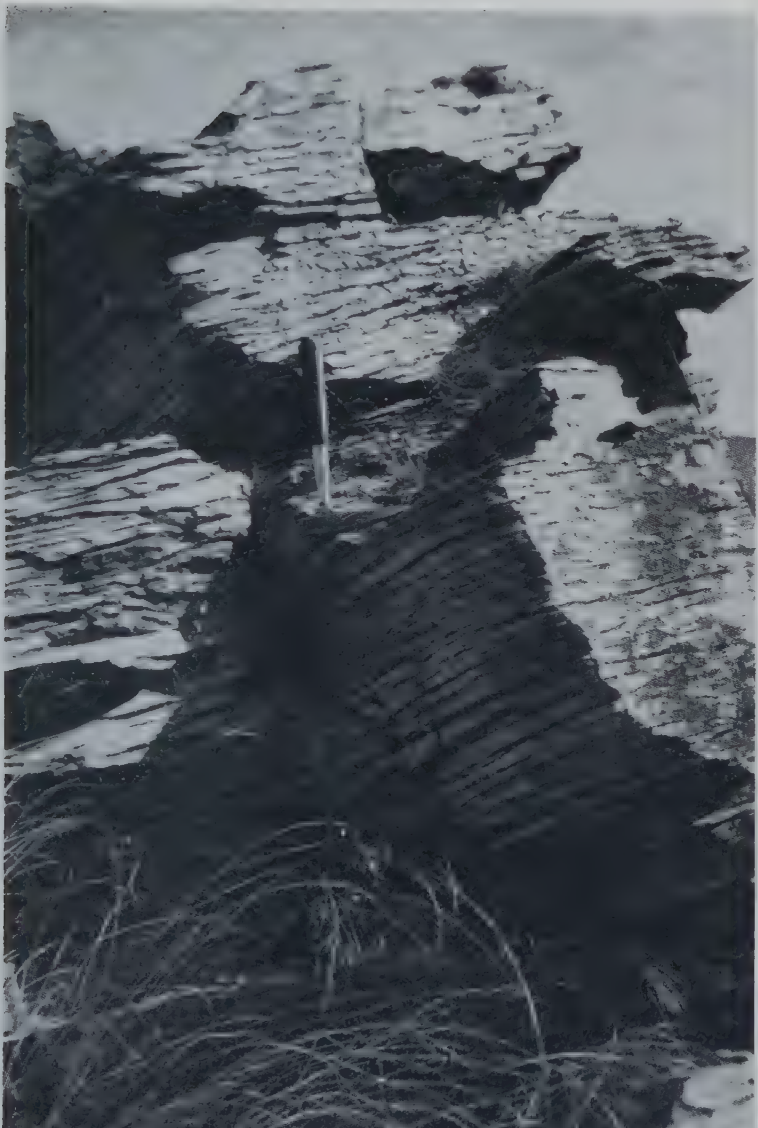

Photo: H. S. Gair

FIG. 3—Typical exposure of Kakanui Schist. Spur to the east of Rugged Ridges Creek, near Trig. U. The strongly layered appearance may be due either to metamorphic segregation or to bedding accentuated by metamorphism. Weathering accentuates this layered appearance and results in a fluted surface with the more resistant quartzo-feldspathic layers forming ridges.

thick are present in most places and are locally very abundant in some of the coarse-grained schists. They are mostly parallel to the schistosity. Samples of the schist submitted to Dr Reed (P22385, P22162, P22163, P22169, P22170, P22171, P22172, P22881) were placed by him (pers. comm.) in the Chlorite 2 sub-zone.

STRUCTURE

The St Mary Fault separates the Kakanui Schist on the north-east from the Mt St Mary Formation on the south-west, and the Wharekuri-Otekaieke Fault brings the Kakanui Schist in contact with either greywacke and argillite of probable Permian age,[5] or Tertiary beds, on the north-east. This horst of schist is an extension of the much larger area of Kakanui Schist west of Oamaru (Gage, 1957, pp. 19–20). It wedges out to the north-west near Aviemore homestead where the faults join. The regional strike and dip of the Kakanui Schist and the Mt St Mary Formation are more or less parallel (see Fig. 1).

The St Mary Fault is best exposed in a small tributary stream from the south-west of Station Creek (1·1, in Fig. 4). This contact shows a 4 ft wide puggy shatter zone between schist and argillite with a 3-in. layer of fault gouge against the argillite. Samples of argillite and schist (P22882, P22881) from either side of the fault here were placed by Dr Reed (pers. comm.) close to the Chlorite 1–2 isograd and probably high Chlorite 2 sub-zone respectively. He also comments that neither samples are good indicators of rank because of their fine grain.

Other exposures in which the actual fault contact is not exposed but in which greywacke or argillite crops out in such proximity to schist as to require a fault occur at the following localities.

Near Aviemore homestead about 100 ft up a 350-ft terrace face, green phyllitic schist adjoins blue-grey argillite (2·2, in Fig. 4). The schist has been shattered, sheared, and rendered talcose over a width of 30 yd near the fault but the argillite has been little affected. Samples of argillite and schist (P23809, P23808) from either side of the fault here were placed by Dr W. A. Watters (pers. comm.) near the Chlorite 1–2 isograd and in the low grade part of the Chlorite 3 sub-zone respectively.

In an exposure on the divide between Parsons Rock Creek and Rugged Ridges Creek schist crops out within 40 yd of argillite. Two samples of the schist (P22162, P22163) were described by Dr Reed (pers. comm.) as quartzo-feldspathic semi-schist derived from greywacke, and phyllite derived from argillite. Both samples were assigned to the Chlorite 2 sub-zone. One sample of the argillite (P22164) was described as semi-schistose argillite probably from the Chlorite 1 sub-zone. Dr Reed considered the metamorphic gap across the fault to be less than one sub-zone.

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[5] McKay (1882, p. 78) found prismatic shell fragments, presumably of *Atomodesma*, at Kurow Hill; their presence has been confirmed by Mr A. R. Mutch and the writers.

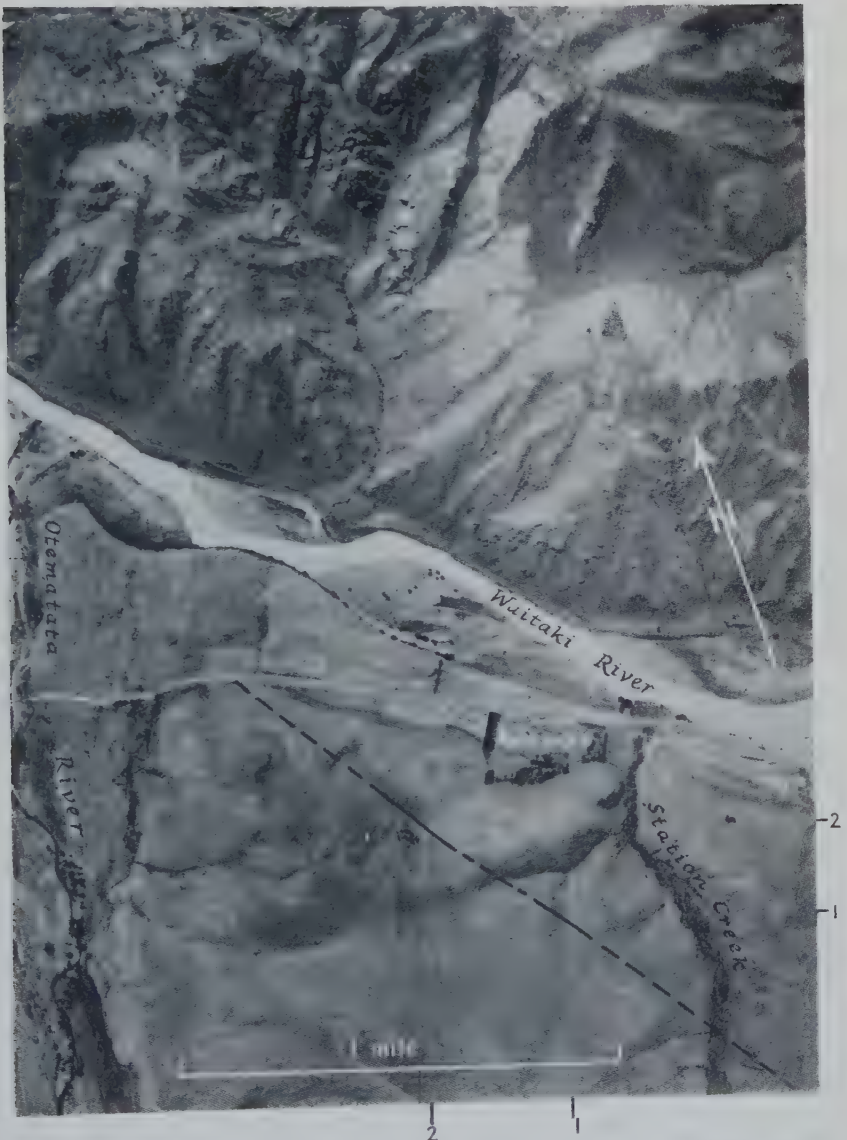

Photo reproduced by permission of Lands and Survey Department

FIG. 4—Vertical air photograph near Aviemore homestead, showing position of St Mary Fault. 1.1, and 2.2, mark exposures of the fault contact.

In Awahokomo Creek section, about 300 yd up from the end of the spur separating the two northernmost tributaries, argillite crops out within 50 ft of schist (5·5, on Fig. 2). As at Aviemore the schist near the fault has been sheared whereas the argillite has been little affected. Dr Reed (pers. comm.) described the argillite (P22386) as probably equivalent to a high Chlorite 1 greywacke and the schist (P22385) as Chlorite 2. He considered the metamorphic gap to be at least three-quarters of a sub-zone and possible one sub-zone.

DISCUSSION

The transition from schist to sedimentary rocks described by Park and Mackie has been used to assign an age little older than Kaihikuan to the rocks metamorphosed to form the Kakanui Schist. As the schist has been shown to be faulted against the sedimentary rocks, it may be appreciably older than Kaihikuan.

It was not found possible to measure the dip of the St Mary Fault plane but from its relatively straight trace irrespective of relief, it can be inferred to be near vertical.

As the metamorphic gap across the St Mary Fault is about one sub-zone, it seems likely that the throw of the fault is several thousand feet. This movement took place in pre-Tertiary time as the fault is truncated by the pre-Tertiary peneplain which forms the north-eastern slopes of the St Mary Range. The Wharekuri-Otekaieke Fault also had some thousands of feet of pre-Tertiary movement but unlike the St Mary Fault it underwent movement during the Tertiary (Marwick, 1935, p. 335) and has moved in the late Quaternary (see Fig. 1).

Mackie (1936, p. 137) attributed the metamorphism of the schists in the Awahokomo to shearing along a thrust parallel to and immediately southwest of the Wharekuri-Otekaieke Fault. The continuity of the schist with the large area of Kakanui Schist near Oamaru mapped by Gage (1957) shows that it is not the result of local shearing but is a true regional schist.

ACKNOWLEDGMENTS

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GRAVITY MEASUREMENTS IN NEW ZEALAND WITH THE CAMBRIDGE PENDULUM APPARATUS

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Summary

A framework of 19 gravity reference stations was established in New Zealand during 1947 and 1948 using the Cambridge pendulum apparatus. The gravity values, relative to Cambridge University (England) as 981 265·0 milligals, were obtained by swinging the six pendulums at Cambridge before and after the New Zealand observations were made. Full details of the results and station locations are given.

Introduction

Relative measurements of gravity with pendulum apparatus rely on the invariability of the physical properties of a set of pendulums which are swung first at a base station and then in the field, the relative values of gravity then being determined from the ratio of the squares of the corrected pendulum periods. Before the introduction of the modern gravity meter, pendulums were used to make detailed gravity surveys, but they are used now only to build frameworks of reference stations within which gravity meters are operated.

The work described here had the aim of providing such a framework of reference stations distributed over the North and South Islands of New Zealand. The Cambridge pendulum apparatus used for the measurements was loaned to the Department of Scientific and Industrial Research by the Department of Geodesy and Geophysics, Cambridge University.

A number of earlier pendulum gravity observations have been made in New Zealand. In 1882 Edwin Smith and H. S. Pritchett of the U.S. Coast and Geodetic Survey swung three Kater pendulums at Auckland (Smith, 1885); in 1903 Otto Klotz of the Astronomical Branch of the Canadian Department of the Interior made observations at Doubtless Bay with two half-second pendulums of Mendenhall's design (Klotz, 1908); in 1901 and 1904 Bernacchi and Skelton of the National Antarctic Expedition observed at Christchurch with the Stückrath apparatus of the South Kensington Museum (Bernacchi, 1908); and in 1910 and 1913 C. S. Wright of the British (Terra Nova) Antarctic Expedition observed at Wellington and Christchurch with the Sterneck pendulum apparatus loaned by the Potsdam Geodetic Institute (Wright, 1921). As far as possible, these sites were re-occupied as part of the framework of reference points established in 1947.

Stations

The nineteen stations were chosen to give a uniform distribution of pendulum measurements throughout New Zealand. Of the stations in the North Island, three were the sites of pendulum measurements by previous observers, and LOWER HUTT was established close to WELLINGTON for gravity meter calibration purposes. The nine stations in the South Island include one site of former observations. The stations cover a range of latitude of about 11°, from 35°S to 46°S, and a range of gravity of about 940 milligals.

The geographical locations of the stations are shown in Figs 1 and 2, detailed station diagrams in Figs 3 and 4, and descriptions of the stations in Appendix A.

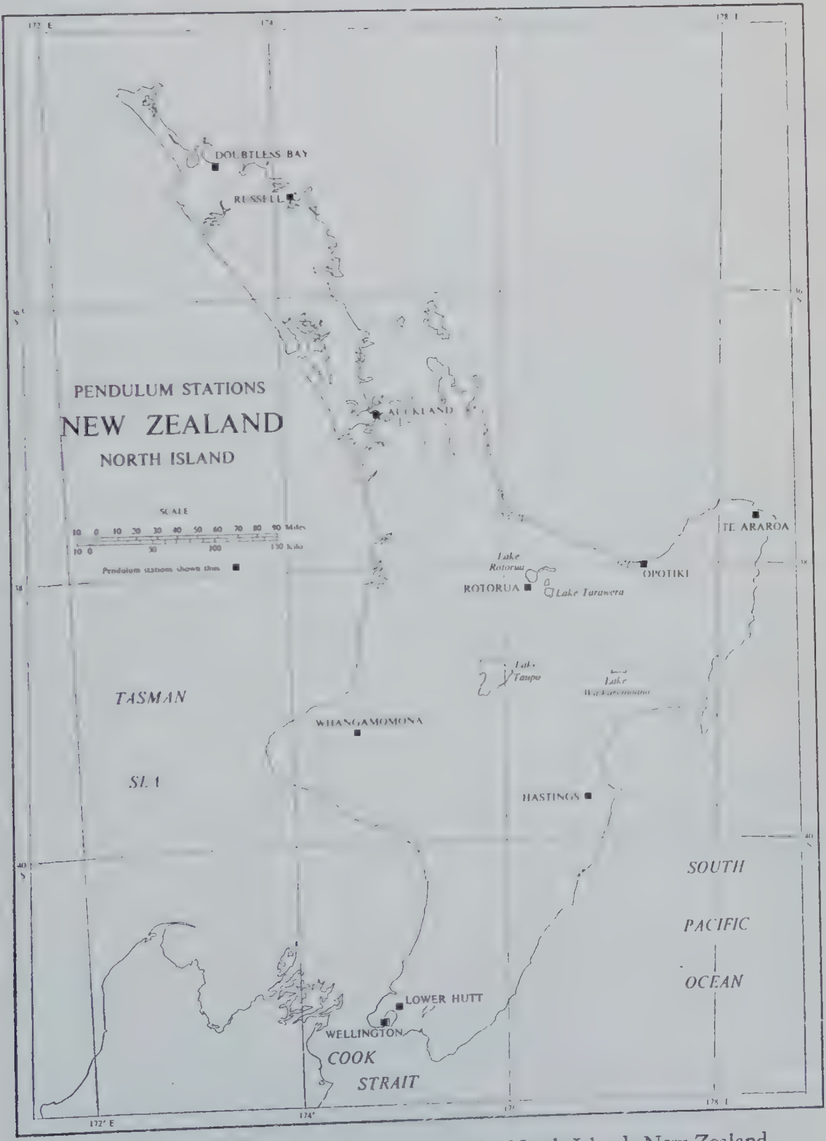

FIG. 1—Location of pendulum stations in the North Island, New Zealand.

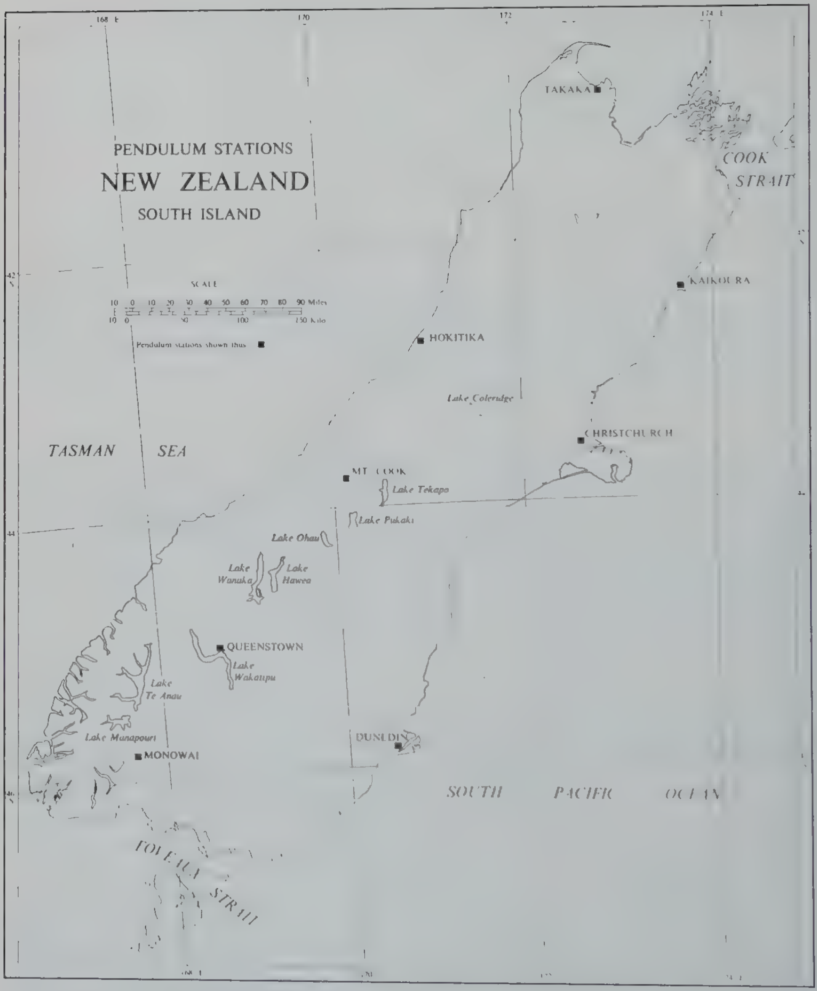

FIG. 2—Location of pendulum stations in the South Island, New Zealand.

APPARATUS

The Cambridge pendulum apparatus used for this work has been fully described by Bullard (1933, 1936). It consists of an aluminium alloy box in which pairs of pendulums are swung in anti-phase under reduced air pressure. The interior of the case is lined with a mu-metal shield to reduce the effect of changes in the earth's magnetic field. The apparatus provides a means of starting the swings with an equal and known amplitude, and also of observing pressure in the case. A dummy pendulum allows an estimate to be made of the pendulum temperature during swinging. Associated equip-

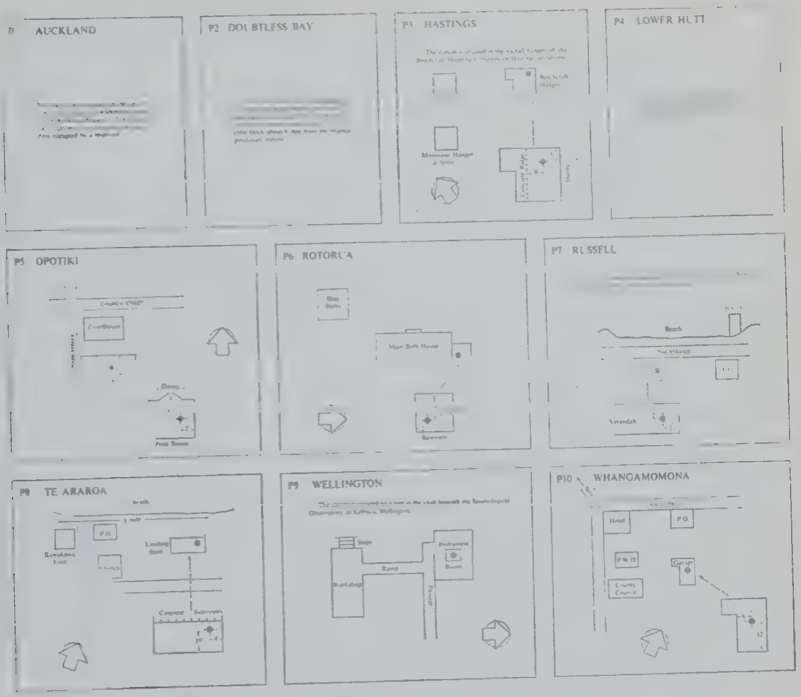

FIG. 3—North Island pendulum station diagrams.

ment included a time marker and a photographic chronograph. The time marker, which serves out pulses of light to time the record of swings, was controlled by a Ferranti portable frequency standard. This standard is not temperature controlled and its frequency has therefore to be properly corrected.

The two sets of three pendulums were made of an alloy of the Invar type, those of set 1 having a bright polish finish and those of set 6 being gilt. The stellite knife-edges support the pendulums on agate planes fixed into the main support box. The pendulums are swung in pairs for about an hour to obtain the required precision and the periods are derived from coincidences on the record of the light signals from the time marker and others made by the reflection of a light spot from prepared surfaces on the pendulum knife edges. The usual practice is to obtain a record of about four minutes' duration at the start and finish of each run.

The calibration of the frequency standard at WELLINGTON in August 1947 showed that the frequency had changed considerably from its CAMBRIDGE value. The New Zealand calibration was therefore used provisionally until the return of the standard to England. The change in frequency was confirmed at CAMBRIDGE in June 1948 and investigation showed that it had been caused by the crystal losing a minute chip. The WELLING-

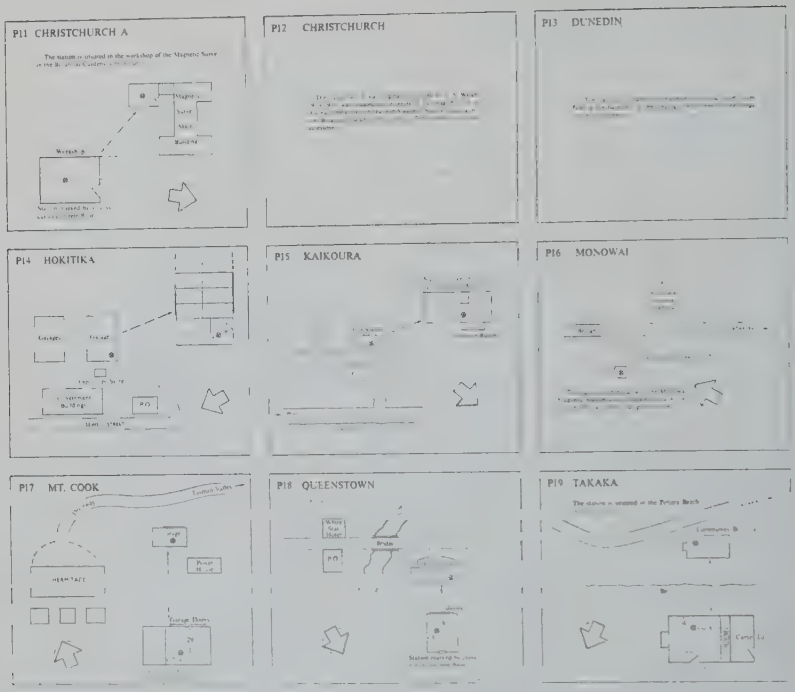

FIG. 4—South Island pendulum station diagrams.

TON calibration also demonstrated that the frequency standard only reached reasonable stability after three days' continuous running. As the tour of each island was expected to last only a few weeks, the standard was therefore run continuously except for the few moments when batteries were being changed.

Pendulums 1A and 1B were once stopped from swinging by the accidental application of the starting lever; however, they appeared to be unaffected by this. No accident of any consequence happened to the pendulums of set 6 or to any other part of the equipment.

OBSERVATIONS

Six pendulums were swung at CAMBRIDGE in May 1947 before they were sent to New Zealand. After the frequency standard had been checked, all six pendulums were swung at WELLINGTON in August 1947. Set 1 was then left there and not swung again until all six pendulums were again swung at the end of the New Zealand programme in November 1947. On return to CAMBRIDGE in June 1948 all six pendulums were again swung there. The results of these observations are shown in Table 1.

The pendulums were always stored and carried in close proximity to the support box and upon their assembly for a run were always left for at least one hour before starting; by this time the thermometer in the dummy pendulum gave a stable reading. At the field stations the pendulum pairs (6A, 6B) and (6A, 6C) were each swung at least twice with the pendulum support box major axis in an E-W direction. The records were read independently by two observers and the observed periods were corrected for temperature, pressure, amplitude and frequency. The residuals of each set of pendulum half-periods were then examined to determine an index of precision for the complete set of measurements at each station. The residuals of the entire set of field station half-periods were also examined to compare the readings of the two observers. The agreement was extremely good, the standard deviations of pendulum half-period for observers 1 and 2 being $2{\cdot}53$ and $2{\cdot}54 \times 10^{-7}$ seconds.

Table 2 shows changes of mean pendulum half-periods during the whole programme. Pendulum 6A had previously shown a consistent instability, but appears to have been quite stable during the present work. The change in 1A is large enough to warrant special treatment in the analysis of the base station periods. By mistake, pendulum 6C was swung in the reverse position for all New Zealand measurements thereby changing its half-period at WELLINGTON by about 16×10^{-7} seconds from the expected value. However, there is no reason why its results should not be accurate as the orientation was consistent for all observations. There are thus only four reasonably stable pendulums to establish the gravity difference between CAMBRIDGE and WELLINGTON, unless one assumes that the change in 1A took place in New Zealand between the two WELLINGTON sets of observations and uses the "before" and "after" periods in conjunction instead of the mean periods. This procedure was adopted in the analysis of the data because of the large difference between the WELLINGTON August and November 1947 half-periods.

RESULTS

The pendulum half-periods are shown in Table 3 together with the standard deviation of the pendulum half-period at each station. The mean of 18 standard deviations for the field stations is $2{\cdot}80 \times 10^{-7}$ seconds. Gravity differences were derived for the field stations by using the mean half-periods of 6A and 6B at CAMBRIDGE in conjunction with the field station values, and combining with these a value obtained with 6C referred to WELLINGTON.* The results from pendulum 6A were assigned a weight twice that of the results from pendulums 6B and 6C.

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*Cook (1957) has shown that the mean period of a pendulum pair is independent of the effects of ground motion, and has suggested that these mean periods be used for computation of gravity differences rather than the periods of individual pendulums. The results have been recomputed on this basis but no value differed by more than 0·1 mgal from the results given in this paper.

TABLE 1—Summary of CAMBRIDGE Half-periods (unit 10^{-7} sec)

	Pendulums		
	1A	1B	1C
May 1947			
18th	5062 312.0		5062 307.5
18th	310.3		306.3
18th	309.5		303.8
19th	314.3	5062 315.7	
19th	314.0	315.5	
19th	312.9	315.4	
Means	5062 312.2	5062 315.5	5062 305.9

	Standard Deviation	Degrees of Freedom
Period	1.71	9
Mean	1.14	4
Difference	0.75	4

	1A	1B	1C
June 1948	5062 297.7	5062 324.0	
	296.5	319.9	
	294.3		5062 308.1
	296.0		308.8
Means	5062 296.1	5062 322.0	5062 308.4

	Standard Deviation	Degrees of Freedom
Period	1.71	5
Mean	1.50	2
Difference	1.53	2

	Pendulums		
May 1947	6A	6B	6C
7th	5054 437.5		5054 442.0
9th	438.2		440.9
9th	*447.9		*450.9
10th	442.8		443.4
11th	433.5	5054 455.7	
12th	435.0	458.3	
12th	437.6	457.9	
12th	*445.3	*453.3	
Means	5054 437.4	5054 457.3	5054 442.1

*Values omitted from means

	Standard Deviation	Degrees of Freedom
Period	2.54	9
Mean	1.68	4
Difference	1.86	4

	6A	6B	6C
June 1948	5054 434.3		5054 444.7
	433.6		444.0
	439.3	5054 454.2	
	428.5	453.8	
Means	5054 433.9	5054 454.0	5054 444.3

	Standard Deviation	Degrees of Freedom
Period	3.43	5
Mean	2.82	2
Difference	5.20	2

Change in mean period	-16.1×10^{-7}	$+6.5 \times 10^{-7}$	$+2.5 \times 10^{-7}$
Means of May 1947 and June 1948 periods used for computing "g"	5062 312.2 5062 296.1	5062 318.7	5062 307.1

NOTE—The pendulum 1A changed by a considerable amount. It was decided to use the initial and final CAMBRIDGE periods in conjunction with the initial and final WELLINGTON periods respectively, instead of using the mean, as with the other pendulums.

Change in mean period	-3.5×10^{-7}	-3.3×10^{-7}	$+2.2 \times 10^{-7}$
Means of May 1947 and June 1948 periods used for computing "g"	5054 435.6	5054 455.6	

NOTE—N.Z. base at WELLINGTON was established with 1A, 1B, 1C, 6A, 6B pendulums, 6C having been swung back to front in N.Z. Pendulum 6C periods were used to obtain "g" values of field stations relative to N.Z. base. The results are incorporated in the field station values.

TABLE 2—Changes in Mean Pendulum Half-periods, May 1947 to June 1948

	1A	1B	1C	6A	6B	6C
May 1947 CAMBRIDGE	5062 312.2	5062 315.5	5062 305.9	5054 437.4	5054 457.3	5054 442.1
August 1947 WELLINGTON	5064 900.1	5064 908.8	5064 894.5	5057 020.4	5057 041.7	5057 044.1*
November 1947 WELLINGTON	5064 887.4	5064 911.2	5064 893.3	5057 023.6	5057 038.8	5057 043.7*
June 1948 CAMBRIDGE	5062 296.1	5062 322.0	5062 308.4	5054 433.9	5054 454.0	5054 444.3

*Not related to others in set – see note in text.

TABLE 3—Pendulum Half-periods at New Zealand Stations (unit 10^{-7} sec)

	Pendulums		
	6A	6B	6C
AUCKLAND	5057 843·6	5057 860·1$_5$	
	841·0	858·8$_5$	
	843·8		5057 866·0
	849·3		864·1
Mean	5057 844·4$_3$	5057 859·5$_0$	5057 865·0$_5$

	Standard Deviation	Degrees of Freedom
Period	2·8$_0$	5
Mean	0·9$_8$	2
Difference	3·7$_6$	2

	6A	6B	6C
DOUBTLESS BAY	5058 219·6$_5$	5058 237·9	
	224·6	239·5$_5$	
	224·5		5058 245·1$_5$
	224·4		244·6
Mean	5058 223·2$_9$	5058 238·7$_3$	5058 244·8$_8$

	Standard Deviation	Degrees of Freedom
Period	2·3$_4$	5
Mean	1·6$_6$	2
Difference	1·6$_9$	2

	6A	6B	6C
HASTINGS	5057 480·2	5057 501·7	
	483·4$_5$	496·6	
	480·8$_5$		5057 502·0$_5$
	481·3$_5$		505·2$_5$
Mean	5057 481·4$_5$	5057 499·1$_5$	5057 503·6$_5$

	Standard Deviation	Degrees of Freedom
Period	2·1$_7$	5
Mean	1·0$_3$	2
Difference	4·6$_6$	2

TABLE 3—Pendulum Half-periods at New Zealand Stations (unit 10^{-7} sec)—*continued*

	Pendulums		
	6A	6B	6C
LOWER HUTT .... (start of programme)	5056 948·8$_5$	5056 967·5	
	951·2$_5$	968·7$_5$	
	952·2	968·8	
	946·9$_5$	965·5$_5$	
	950·0$_5$		5056 972·7
Mean	5056 949·8$_6$	5056 967·6$_6$	5056 972·7
	Standard Deviation		Degrees of Freedom
Period	1·8$_5$		7
Mean	1·9$_3$		3
Difference	0·9$_7$		3
LOWER HUTT .... (middle of programme)	5056 951·0	5056 967·0$_5$	
	951·4$_5$	968·9	
	949·0		5056 972·4$_5$
	951·5		972·9$_5$
Mean	5056 950·7$_4$	5056 967·9$_8$	5056 972·7$_0$
	Standard Deviation		Degrees of Freedom
Period	1·1$_0$		5
Mean	0·9$_5$		2
Difference	1·2$_2$		2
OPOTIKI	5057 709·4	5057 683·8$_5$	
	694·1	701·1	
	687·0		5057 710·9
	702·6$_5$		701·4
Mean	5057 698·2$_9$	5057 692·4$_8$	5057 706·1$_5$
	Standard Deviation		Degrees of Freedom
Period	9·8$_1$		5
Mean	1·6$_2$		2
Difference	20·5$_7$		2
ROTORUA	5057 797·1	5057 808·7	
	798·0	801·5$_5$	
	803·0		5057 812·2
	799·6		809·5$_5$
Mean	5057 799·4$_3$	5057 805·1$_8$	5057 810·8$_8$
	Standard Deviation		Degrees of Freedom
Period	3·1$_4$		5
Mean	2·1$_7$		2
Difference	5·5$_8$		2
RUSSELL	5058 161·3	5058 177·9$_5$	
	160·0$_5$	176·2	
	161·5$_5$		5058 177·6$_5$
	163·1$_5$		181·8
Mean	5058 161·5$_1$	5058 177·0$_8$	5058 179·7$_3$
	Standard Deviation		Degrees of Freedom
Period	1·7$_3$		5
Mean	1·6$_2$		2
Difference	1·3$_0$		2

TABLE 3—Pendulum Half-periods at New Zealand Stations (unit 10^{-7} sec)—*continued*

	Pendulums		
	6A	6B	6C
TE ARAROA	5057 931.1$_5$	5057 952.2$_5$	
	933.8$_5$	956.7$_5$	
	937.4$_5$		5057 962.1$_5$
	944.8$_5$		958.4
Mean	5057 936.8$_3$	5057 954.5$_0$	5057 960.2$_8$

	Standard Deviation	Degrees of Freedom
Period	4.9$_6$	5
Mean	2.0$_2$	2
Difference	5.6$_5$	2

	1A	1B	1C
WELLINGTON .... (start of programme)	5064 900.3	5064 906.5$_5$	
	900.8$_5$	911.1	
	899.1$_5$		5064 894.5
	900.1		894.4$_5$
Mean	5064 900.1$_0$	5064 908.8$_3$	5064 894.4$_8$

	Standard Deviation	Degrees of Freedom
Period	1.5$_3$	5
Mean	1.3$_0$	2
Difference	2.0$_6$	2

	1A	1B	1C
WELLINGTON .... (end of programme)	5064 889.2$_5$	5064 911.4$_5$	
	887.7	910.9$_5$	
	885.2$_5$		5064 893.7$_5$
	887.2$_5$		892.9
Mean	5064 887.3$_8$	5064 911.2$_0$	5064 893.3$_3$

	Standard Deviation	Degrees of Freedom
Period	2.9$_4$	5
Mean	0.5$_9$	2
Difference	1.5$_4$	2

	6A	6B	6C
WELLINGTON .... (start of programme)	5057 019.3$_5$	5057 041.9	
	021.6$_5$	041.4$_5$	
	019.8$_5$		5057 043.6
	020.8		044.6
Mean	5057 020.4$_1$	5057 041.6$_8$	5057 044.1$_0$

	Standard Deviation	Degrees of Freedom
Period	0.8$_6$	5
Mean	0.6$_7$	2
Difference	1.3$_8$	2

TABLE 3—Pendulum Half-periods at New Zealand Stations (unit 10^{-7} sec)—*continued*

	Pendulums		
	6A	6B	6C
WELLINGTON (end of programme)	5057 022.6$_5$	5057 038.8	
	022.5$_5$	038.7$_5$	
	024.9		5057 043.5$_5$
	024.1		043.9
Mean	5057 023.5$_5$	5057 038.7$_8$	5057 043.7$_3$
	Standard Deviation		Degrees of Freedom
Period	0.8$_9$		5
Mean	0.1$_3$		2
Difference	0.5$_8$		2
WHANGAMOMONA	5057 510.9$_5$	5057 523.7$_5$	
	511.5	523.5	
	514.7		5057 528.8
	512.4$_5$		529.5
Mean	5057 512.4$_3$	5057 523.6$_3$	5057 529.1$_5$
	Standard Deviation		Degrees of Freedom
Period	1.2$_9$		5
Mean	0.4$_0$		2
Difference	1.4$_9$		2
CHRISTCHURCH A	5056 393.5	5056 410.0	
	403.6$_5$	407.6$_5$	
	403.6		5056 412.3$_5$
	398.6$_5$		415.5$_5$
Mean	5056 399.8$_5$	5056 408.8$_3$	5056 413.9$_5$
	Standard Deviation		Degrees of Freedom
Period	3.9$_5$		5
Mean	2.0		2
Difference	7.4$_6$		2
CHRISTCHURCH	5056 400.8	5056 412.7	
	399.8	415.5	
	399.7	413.5$_5$	
	397.7		5056 416.4$_5$
	398.8		412.8$_5$
Mean	5056 399.3$_6$	5056 413.9$_2$	5056 414.6$_5$
	Standard Deviation		Degrees of Freedom
Period	1.5$_1$		7
Mean	0.8$_4$		3
Difference	2.4$_7$		3
DUNEDIN	5055 795.6	5055 813.9$_5$	
	793.3	813.4	
	799.1$_5$		5055 820.2$_5$
	795.2$_5$		819.2$_5$
Mean	5055 795.8$_3$	5055 813.6$_8$	5055 819.7$_5$
	Standard Deviation		Degrees of Freedom
Period	1.8$_7$		5
Mean	1.4$_2$		2
Difference	1.7$_0$		2

TABLE 3—Pendulum Half-periods at New Zealand Stations (unit 10^{-7} sec)—*continued*

	Pendulums		
	6A	6B	6C
HOKITIKA	5056 648.1$_5$	5056 655.3$_5$	
	652.5	654.6	
	643.2$_5$	661.2$_5$	
	647.3$_5$		5056 668.5
	643.7$_5$		666.7$_5$
Mean	5056 647.0$_0$	5056 657.0$_7$	5056 667.6$_3$
	Standard Deviation		Degrees of Freedom
Period	3.4$_7$		7
Mean	2.0$_4$		3
Difference	10.1$_0$		3
KAIKOURA	5056 735.0$_5$	5056 751.6$_5$	
	733.5	750.3	
	730.3$_5$		5056 759.2$_5$
	730.5$_5$		758.2$_5$
Mean	5056 732.3$_6$	5056 750.9$_8$	5056 758.7$_5$
	Standard Deviation		Degrees of Freedom
Period	1.8$_6$		5
Mean	0.7$_6$		2
Difference	0.6$_1$		2
MONOWAI	5056 025.6$_5$	5056 043.8	
	023.7	046.0$_5$	
	028.4$_5$		5056 048.3
	025.2$_5$		051.6
Mean	5056 025.7$_6$	5056 044.9$_8$	5056 049.9$_5$
	Standard Deviation		Degrees of Freedom
Period	1.9$_9$		5
Mean	0.0$_8$		2
Difference	3.8$_7$		2
MT COOK	5057 009.7$_5$	5057 024.1$_5$	
	008.1$_5$	024.3$_5$	
	007.8$_5$		5057 028.1
	011.3		026.3
Mean	5057 009.2$_6$	5057 024.2$_5$	5057 027.2$_0$
	Standard Deviation		Degrees of Freedom
Period	1.3$_6$		5
Mean	0.5$_4$		2
Difference	2.6$_9$		2
QUEENSTOWN	5056 410.6	5056 422.9	
	408.7$_5$	423.4	
	414.4$_5$		5056 428.4
	413.0$_5$		427.0
Mean	5056 411.7$_1$	5056 423.1$_5$	5056 427.7$_0$
	Standard Deviation		Degrees of Freedom
Period	2.0$_8$		5
Mean	0.7$_8$		2
Difference	1.1$_8$		2

TABLE 3—Pendulum Half-periods at New Zealand Stations (unit 10^{-7} sec)—*continued*

	Pendulums		
	6A	6B	6C
TAKAKA	5056 999.6	5057 016.1$_5$	
	5057 001.5	017.4$_5$	
	007.2$_5$		5057 016.9
	002.5$_5$		5057 014.1$_5$
Mean	5057 002.7$_8$	5057 016.8	5057 015.5$_2$

	Standard Deviation	Degrees of Freedom
Period	2.7$_0$	5
Mean	2.5$_0$	2
Difference	1.0$_2$	2

The gravity difference between CAMBRIDGE and WELLINGTON was obtained from the mean periods of five pendulums (1A, 1B, 1C, 6A and 6B) using the CAMBRIDGE periods in the same way as for the field stations, and giving the A pendulums twice the weight of the others. The standard deviation of this difference for any one pendulum is 0·61 mgal and the adopted value is therefore accurate to one milligal expressed at the 99% confidence level. The observed values of gravity at the New Zealand stations relative to CAMBRIDGE g = 981 265·0 mgal (Bullard and Jolly, 1936) are given in Table 4.

TABLE 4

	Station	Latitude S		Longitude E		Height	Gravity
		°	′	°	′	m	gal
P 1	AUCKLAND	36	51.8	174	46.7	79	979.943$_3$
P 2	DOUBTLESS BAY	34	59.5	173	29.1	7	979.796$_4$
P 3	HASTINGS	39	39.2	176	46.0	20	980.083$_6$
P 4	LOWER HUTT	41	14.2	174	55.0	3	980.289$_5$
P 5	OPOTIKI	38	00.4	177	17.1	10	980.003$_2$
P 6	ROTORUA	38	08.3	176	15.5	286	979.962$_6$
P 7	RUSSELL	35	15.9	174	07.3	5	979.820$_7$
P 8	TE ARAROA	37	38.1	178	22.3	5	979.907$_0$
P 9	WELLINGTON	41	17.2	174	46.1	122	980.261$_8$
P10	WHANGAMOMONA	39	08.8	174	44.2	156	980.072$_8$
P11	CHRISTCHURCH A	43	31.8	172	37.2	7	980.504$_6$
P12	CHRISTCHURCH	43	31.8	172	37.2	5	980.504$_1$
P13	DUNEDIN	45	52.0	170	39.0	10	980.737$_0$
P14	HOKITIKA	42	43.2	170	57.7	2	980.408$_1$
P15	KAIKOURA	42	24.4	173	40.9	6	980.373$_5$
P16	MONOWAI	45	47.1	167	37.3	165	980.647$_7$
P17	MT COOK	43	44.2	170	05.5	748	980.267$_3$
P18	QUEENSTOWN	45	02.0	168	39.4	314	980.499$_5$
P19	TAKAKA	40	49.9	172	53.1	3	980.270$_4$

The above values should be considered accurate to one milligal but are given to 0·1 mgal for purposes, such as the calibration of gravity meters, where the gravity differences before rounding off may be required for the New Zealand stations.

The values of gravity given in Table 4 have not been corrected for the magnetic effect of the invar pendulums. Cook (1954) considers that the correction for the WELLINGTON-CAMBRIDGE interval is + 0·3 mgal. This does not change the value of 980·262 gals which has been adopted for the New Zealand base station at WELLINGTON.

Since 1947–48, a network consisting of the 19 pendulum stations and an additional 418 stations has been established using a North American gravity meter; and G. P. Woollard of the University of Wisconsin and his collaborators have made a number of measurements of the gravity difference between New Zealand and Washington, U.S.A., with both Worden gravity meters and Gulf pendulum apparatus. A complete analysis of this data and the values of gravity on the Potsdam system has been published by Robertson and Reilly (1960) who also published a Bouguer anomaly map of New Zealand in 1958.

ACKNOWLEDGMENTS

The authors are indebted to Dr E. C. Bullard of the Department of Geodesy and Geophysics, Cambridge University, for lending the Cambridge pendulum apparatus and taking an interest in all aspects of the work.

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APPENDIX A

DESCRIPTIONS OF PENDULUM STATIONS

P 1 AUCKLAND

On the step of the 'Transit of Venus' monument in the Domain to the south of the Auckland Museum. The site occupied in 1882 by Smith and Pritchett was in a brick building a short distance from this station. Both sites are now lost following extensive excavations in the vicinity.

P 2 DOUBTLESS BAY

On a concrete block, 12 cm thick, near the Cable Station at Doubtless Bay. The site was estimated to be within 2 m of the original position occupied by Klotz in 1903.

P 3 HASTINGS

In the hangar of the Beechcraft Mapping Company at Bridge Pa Aerodrome, Hastings.

P 4 LOWER HUTT

In the Electrical Standards Laboratory of the Dominion Physical Laboratory at Gracefield, Lower Hutt.

P 5 OPOTIKI

In the Print Room attached to the Courthouse at Opotiki.

P 6 ROTORUA

In a disused basement at the rear of the Government Bath House at Rotorua.

P 7 RUSSELL

On the concrete verandah of Bishop Pompallier's house which is now a museum at Russell.

P 8 TE ARAROA

On a loading bank about 800 m east of the Kawakawa Hotel at Te Araroa.

P 9 WELLINGTON

In an instrument room situated underground below the Seismological Observatory (previously called Dominion Observatory) in Wellington. This site was occupied by C. S. Wright in 1910 and 1913.

P 10 WHANGAMOMONA

In the garage at the rear of the County Council Chambers in Whangamomona.

P 11 CHRISTCHURCH A

In the workshop at the rear of the Magnetic Survey building in the Botanical Gardens, Christchurch. This is one of the First Order Gravity Stations in the world network. This station is called CHRISTCHURCH (new) by Cook (1957).

P 12 CHRISTCHURCH

In the cellar of the old variometer house of the Magnetic Survey in the Botanical Gardens, Christchurch. This site which was occupied by C. S. Wright in 1910 and 1913 is now lost following extensions to a nearby building. This station is called CHRISTCHURCH (old) by Cook (1957).

P 13 DUNEDIN

In the basement of the Geology Department at the University of Otago in Dunedin.

P 14 HOKITIKA

In the garages at the rear of the Government Buildings in Sewell Street in Hokitika.

P 15 KAIKOURA

In the Fire Brigade Station at Kaikoura.

P 16 MONOWAI

On a 1·2 × 1·2 m concrete block near the junction of the Tuatapere - Te Anau road and the road leading to the Monowai hydroelectric power station.

P 17 MOUNT COOK

In the garage near the Power House at the Mt Cook Hermitage.

P 18 QUEENSTOWN

In the P. and T. Garages in Queenstown.

P 19 TAKAKA

In the community building of the Pohara Beach Motor Camp about 8 km from Takaka.

THE OTAMITAN STAGE (TRIASSIC): DEFINITION AND TYPE LOCALITY

By J. D. CAMPBELL, University of Otago, Dunedin, and I. C. MCKELLAR, New Zealand Geological Survey, Department of Scientific and Industrial Research, Dunedin.

(Received for publication, 22 April 1960)

Summary

The Otamitan Stage is defined and the sequence at the type locality (Otamita Stream, Hokonui Hills) is described. Fossils recorded and described from Otamitan horizons are listed.

INTRODUCTION

In setting up the Otamitan Stage Marwick (1951, 1953) nominated the Otamita Stream section south-west of Mandeville (Fig. 1) as type. This section includes some of the most richly fossiliferous rocks in the Triassic of New Zealand and although it has received attention from a number of workers, finer points of sequence and structure are not to be found in the literature. Separately and together, the writers have examined the section in detail and can subdivide the sequence into lithological units that are mappable over at least short distances. Faunal succession is reasonably well established although recognition of zones other than that of *Mytilus problematicus* is considered premature even in this, the most abundantly fossiliferous New Zealand Triassic stage. Recognition of a fault interrupting the succession in the main stream section at Otamita leads us to use the exposures along a tributary of Otamita Stream for the lower part of the type section.

The writers are grateful to Dr P. B. Maling of Christchurch who in 1934 collected extensively in the Hokonui Hills and at Otamita in particular, where his careful work led to the drawing of a map – regrettably never published – which with MS notes he has kindly made available, and are also grateful for the help and company of field companions on several trips.

The aerial photograph is reproduced with the permission of the Surveyor-General.

One of the writers (J.D C.) is responsible for the paleontology in this paper while structure is more especially the work of the other (I.C.McK.).

HISTORICAL

Marshall (1909) was the first to describe fossils from the Otamita Stream section although private correspondence (held by the Geological Survey, Dunedin) shows that R. A. S. Browne discovered the richly fossiliferous beds in Otamita Stream in 1901.

N.Z. J. Geol. Geophys. 3 : 643–59

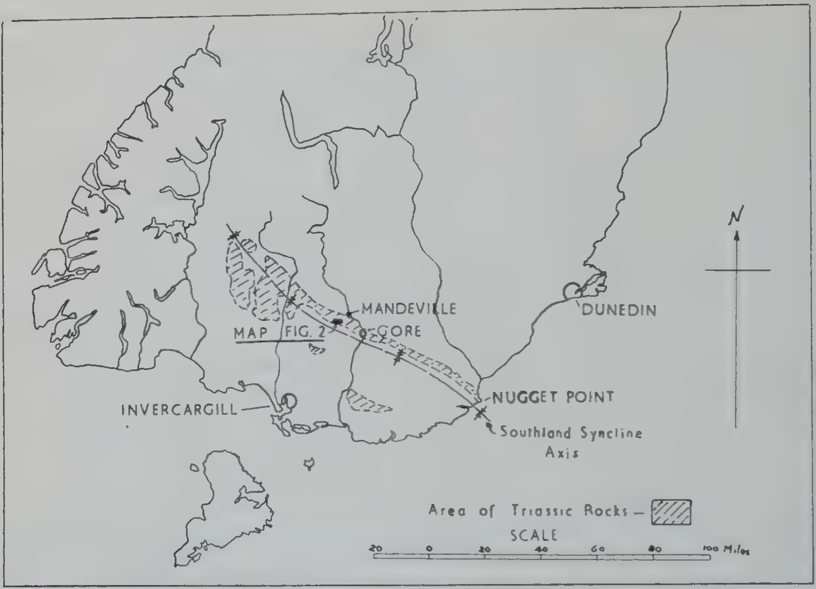

FIG. 1—Locality map of the southern part of the South Island, New Zealand, showing the area covered by the map, Fig. 2, and its relation to the main area of Triassic rocks outcropping along the north limb of the Southland Syncline.

In their survey of the Hokonui Hills, Cox (1878) and McKay (1878) did not find the *Mytilus problematicus* beds and the map accompanying Cox's report is inaccurate in the region about Otamita Valley. (The map, redrawn but uncorrected, is reproduced in Marwick, 1953). Cox's Upper Wairoa Series accommodated the rocks now included in Otamitan Stage.

Marshall (1909) described two species of cephalopods collected by himself and R. A. S. Browne from an outcrop in Otamita Valley. The locality recorded by Marshall, "behind Mandeville," was vague, but happily, Thomson (1913, p. 15) reported Marshall's verbal description of the locality in a footnote and this leaves no doubt that the collection was made in Otamita Valley and that the horizon was Otamitan.

Trechman (1918), after visiting the Otamita Valley with Marshall, summarised the sequence in a column and described and recorded over 30 species of brachiopods and molluscs collected there. Trechmann's column (*ibid.*, p. 178) consists of a series of beds (lettered a, b, c, etc.) but some of these cannot be recognised in the field with certainty. It is clear, however, that large collections* were made from:

(1) an outcrop on the left bank of the Otamita Stream in the north-flowing reach of part of the course commonly referred to as the "S-bend" (S169/834);

(2) an outcrop on the right bank of Otamita Stream, $\frac{3}{4}$ mile further downstream and somewhat higher in the sequence (S169/816).

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*A MS map, drawn by R. A. S. Browne, and held by Mr G. Stevenson, Dacre, shows Trechmann's main collecting site and other richly fossiliferous localities.

Wilckens (1927) described two pelecypod species from Nelson Otamitan localities and figured and recorded other Otamitan fossils from Nelson and South Otago.

Williamson (1932) set up a unit, Whakahau Series with type locality at Marakopa, equivalent to the lower part of Wairoa Series of Hector and defined to include rocks that would now be placed in Otamitan Stage.

Ongley (1933), in subdividing Wairoa Series, nominated Otamita Stream section as described by Trechmann as type locality for his Otamita Series (McKellar, 1959). Marwick (1951, 1953), gave this unit stage status and retained Otamita Stream as the type section.

Kummel (1953) decribed a nautiloid from Otamita.

Campbell (1959) summarised the fauna and distribution of the Otamitan Stage.

DEFINITION

The Otamitan Stage is here defined as those beds laid down at the type locality after the appearance of *Mytilus problematicus* Zittel and before the appearance of a post-Otamitan fauna. The stage consists of approximately 1,340 ft of sandstone, siltstone and tuff between localities S169/822 and S169/844 (see Figs. 2, 3, 4).

In the type section the following are not known to extend vertically beyond the limits of the Otamitan Stage as defined above:

Terebratula pachydentata Trechmann
Spiriferina otamitensis Trech.
Athyris manzavinioides (Trech.)
Nuculana semicrenulata (Trech.)
Paleoneilo otamitensis Trech.
Myophoria otamitensis Trech.
Cassianella sp.
Pseudoplacunopsis placentoides Trech.
Mytilus problematicus Zittel
M. mirabilis Trech.
Tutcheria parvula (Trech.)
Palaeocardita quadrata Trech.
Pleurotomaria hokonuiensis Trech.
P. (Sisenna) hectori Trech.
Lepidotrochus marshalli Trech.

The following are apparently restricted in stratigraphic range to sections other than the type section shown in Figs. 3, 4 that are Otamitan by correlation:

Spiriferina (Rastelligera) acutissima Trechmann
Myophoria heslingtonensis Trech.
Zygopleura sp.
Atlantobellerophon zealandicus Trech.

OTAMITA VALLEY

There is little doubt that Marwick (1953, p. 15), intended that the section exposed along Otamita Stream itself (Figs. 1, 2) should be the type of his Otamitan Stage although he was careful to avoid selection of a particular line of section. Trechmann's (1918, p. 178) column was compiled

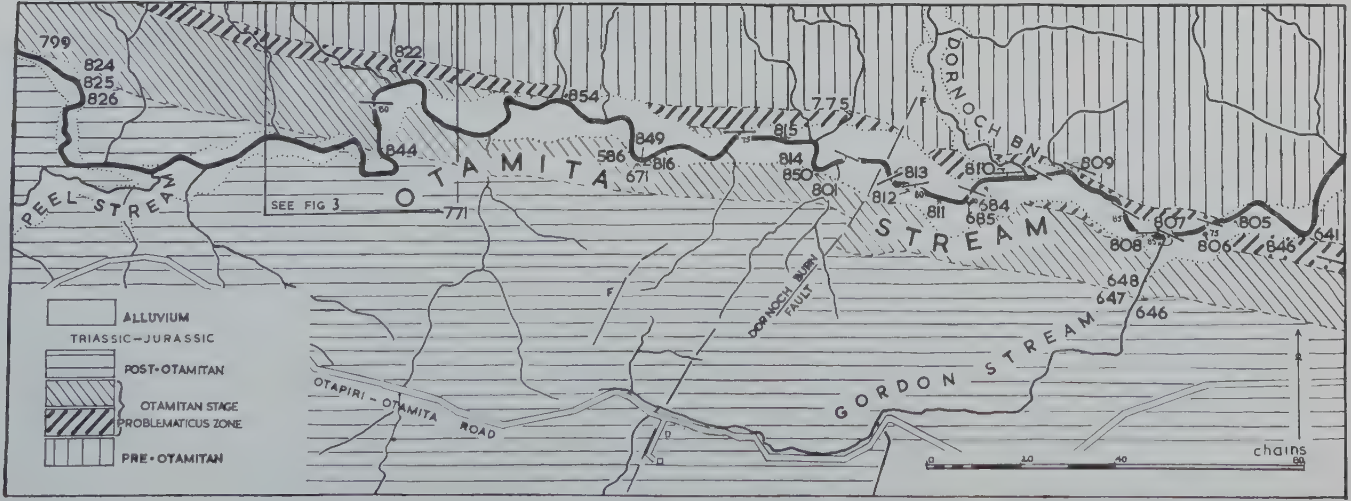

FIG. 2—Geological map of the part of the Otamita Valley discussed in this paper. For location see Fig. 1. The Otamita Stream flows from west to east and continues out to the north margin of the Hokonui Hills at Mandeville, about four miles north-east of the mouth of Gordon Stream. Location of fossil collections, all within N.Z.M.S. Sheet S. 169, are shown by sheet fossil members. Topography is from aerial photo plots compiled by N.Z. Geological Survey. Further details in the neighbourhood of the S-bend are shown in Fig. 3.

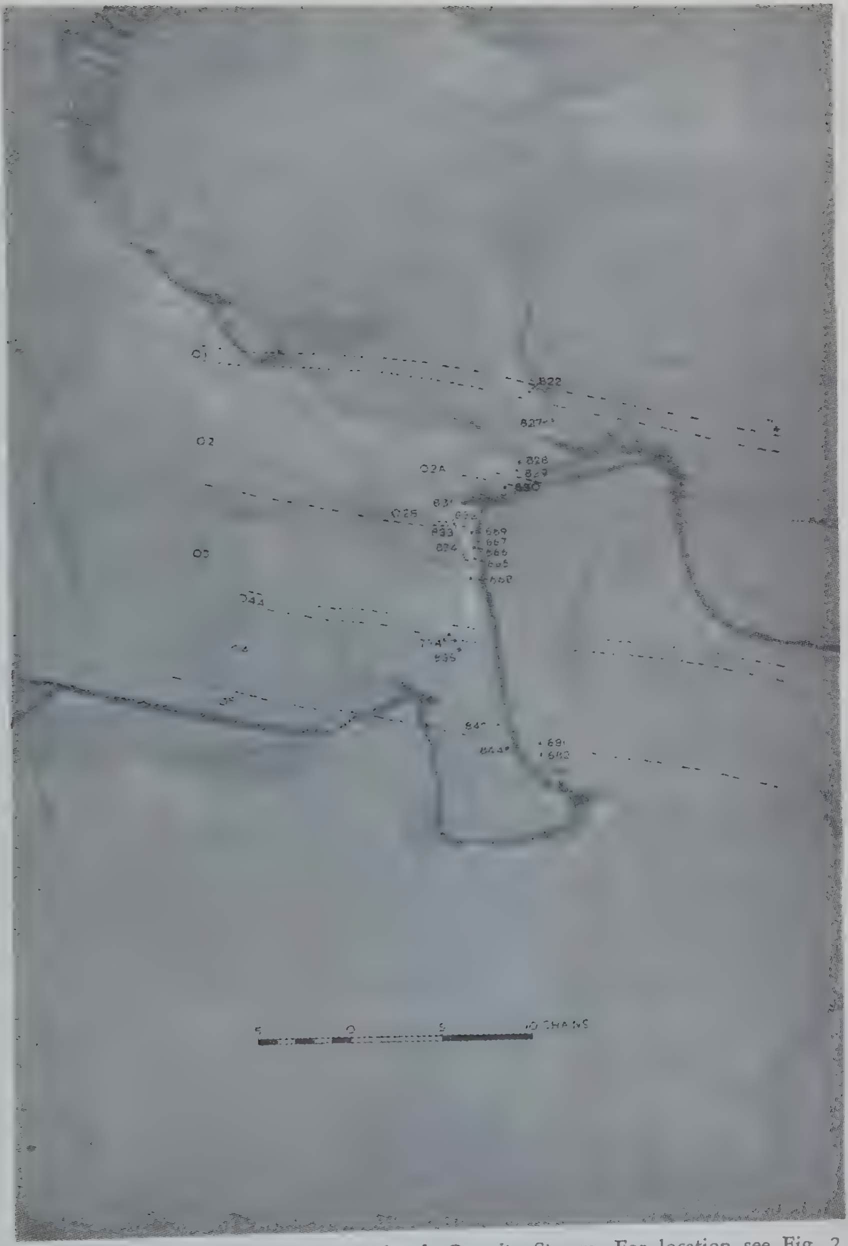

FIG. 3—Aerial photograph of the S-bend, Otamita Stream. For location see Fig. 2. Beds stand vertical or dip steeply south throughout this area. Limits of formations 0.1–5 are shown

0.2A = S-bend Sandstone Member
0.2B = S-bend Brachiopod Sandstone Member
0.4A = Grey Sandstone Member

Fossil localities marked by sheet fossil numbers, all in N.Z.M.S. Sheet S. 169.

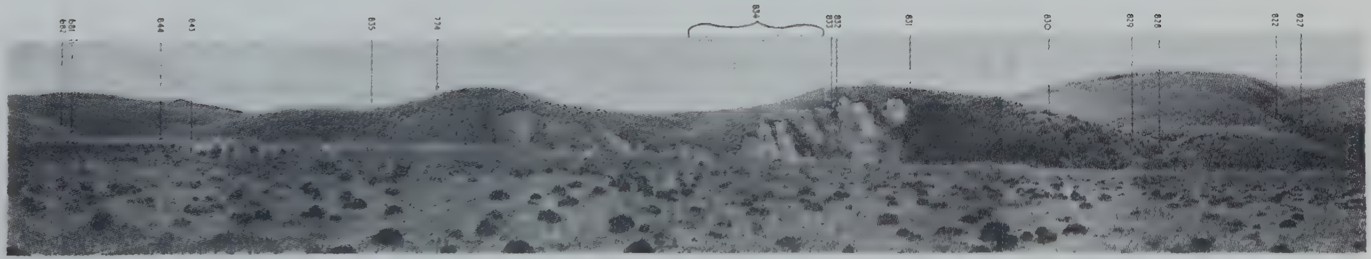

FIG. 4—Panorama of type section of the Otamitan Stage on the west bank of the Otamita Stream along the central north flowing reach of the S-bend. The stream is entrenched along the far edge of the tussock flats in the foreground, and flows from left to right. In the centre of the panorama the observer looks west. Fossil localities are shown by sheet fossil numbers, and limits of formations may be found by referring to Figs. 3 and 5.

from exposures in the main stream but the sequence as such cannot be found in any one section and the column must therefore have been based on a composite section. The writers had hoped to select a type section in the main stream of the Otamita from near the junction of Gordon Stream to the upstream end of the S-bend such that a well-exposed sequence through Otamitan beds could be demonstrated. Careful examination of the outcrops in the main valley has failed to produce such a section. The length along the main stream between the most nearly contiguous exposures of basal and uppermost Otamitan is over 4 miles, an unwieldy length of section for 1,340 ft of nearly vertical beds and further, Otamitan beds are faulted within this section. The type section selected includes rocks exposed in a tributary valley. In justification of this and for completeness, a detailed account is given below of Otamitan exposures in the Otamita Valley between Gordon and Peel Streams.

Gordon Stream to Dornoch Burn

Otamita Stream meanders across narrow river flats (Fig. 4) in this part of its course and is entrenched into bedrock in most places with the more resistant beds forming rock bars and buttresses and steep faces up to 10 ft high giving discontinuous exposures.

Downstream and east of its junction with Gordon Stream, Otamita Stream crosses rocks crowded with *Mytilus problematicus*. These beds form part of the *problematicus* zone which is more completely exposed in the type section of the stage. Here, however, the point of incoming of *M. problematicus* can be determined. The fossil occurs as crowded separated valves in siltstone which forms conspicuous ribs in the stream (S169/806). Similar shell beds crop out at the junction of Gordon Stream (S169/807, 808) some 400 ft above the incoming of *M. problematicus*. The two bands of shell bed are separated by flinty, tuffaceous beds and a sandstone which appear to be unfossiliferous and which form low ribs. A 15-ft zone of contorted bedding and a minor local unconformity are exposed here. About 30 chains east of the Gordon Stream junction siltstones with *Halobia* sp. and rare *Oretia* sp. make up low ribs in Otamita Stream (S169/805). These rocks underlie the *problematicus* zone and are correlated with the Oretian Stage.

It is probable that the top of the *problematicus* zone is stratigraphically higher than S169/808 but the overlying beds are obscured and the reach of Otamita Stream above Gordon Stream junction cuts into older beds of the *problematicus* zone. In the half mile upstream from the Gordon junction the section is followed down to the base of the *problematicus* zone (S169/809) where the key fossil is associated with plant remains along with:

Athyris cf. *wreyi* (Suess)
Halobia sp.
Rhacophyllites sp.

Dornoch Burn to Peel Stream

Immediately west of the mouth of Dornoch Burn, shell beds with *M. problematicus* are crossed by Otamita Stream (S169/810) and again 13 chains upstream from Dornoch Burn (S169/685). At an intermediate point 10 chains upstream from Dornoch Burn (S169/684) the following fauna occurs:

Halobia sp.
Hokonuia limaeformis Trech.
Chlamys sp.
Mytilus problematicus Zitt.
Rhacophyllites sp.

The locality from which Marshall described *Arcestes hokonui* and *Bronco-ceras mandevillei (Proclydonautilus)* has not been relocated with certainty for although S169/684 agrees well with the description in Thomson (1913, p. 15) the annotated sketch map by R. A. S. Browne, referred to above, associates arcestids and large nautiloids with a locality S169/801 somewhat west of S169/684 and recent collections from the latter locality confirm this (see below).

Mytilus problematicus beds are intercepted by a south-flowing reach of the stream 29 chains west of Dornoch Burn (S169/813). The strike of 60° would carry rocks of the *problematicus* zone south of the stream west of S169/813. Rocks of this zone do not appear on the south side of the Otamita at any point west of this locality. The discontinuity of the *problematicus* zone rocks is accounted for by postulating a clockwise transcurrent fault, here named the Dornoch Burn Fault with a shift of 300–400 ft. It was first mapped by P. B. Maling who recognised it on stratigraphic grounds (MS written in 1934 and now held by J. D. C.). Independent evidence of this fault can be found to the south-west on the north slopes of Mt Peel and to the north-east in the head of Dornoch Burn and Home Stream.

East of the Dornoch Burn Fault the strike varies between 60° and 105°. From the fault westwards to the S-bend the strike direction is almost constant (95°–100°) and there are no structural complications.

Otamita Stream exposes rocks of the highest beds of the *problematicus* zone at one point (S169/854) between Dornoch Burn Fault and the S-bend but all other exposures in this part of the stream's course are in Otamitan rocks deposited after the disappearance of *M. problematicus*. Some of these exposures will be referred to below in the description of the type section.

Type Section of Otamitan Stage

The stream section exposed along the north-flowing central reach of the S-bend and in the tributary stream to the north is here nominated type section of the Otamitan Stage (Figs. 2, 3, 4). It has been possible to subdivide the Otamitan rocks of this section into lithological units as shown in Figs. 3, 5 and these units constitute four formations each with its type locality in this section:

Formation	Content	Trechmann (1918)
0·4	Sandstone including plant-bearing sandstone	?bed b
0·3	Siltstone (Trechmann Concretionary Siltstone)	beds e, d, c
0·2	Sandstone with minor siltstone (S-bend Sandstone, S-bend Brachiopod Sandstone, etc.)	
0·1	Siltstone with shell beds (Problematicus Siltstone)	bed f

Formation 0.1: Problematicus Siltstone

The formation is about 100 ft thick and is composed of siltstone, minor sandstone, and locally silicified tuff. Included in the siltstone are shell beds of the order of 10–40 ft thick with innumerable separated valves, complete or fragmentary, of *Mytilus problematicus*, *Halobia* sp. and, in lesser abundance, other pelecypods. Brachiopods, especially athyrids and dielasmids are not uncommon in the shell beds and are generally preserved with valves conjoined. The formation is recognised by the distinctive shell beds and in fact is to be distinguished from other siltstones by its fossils which are here treated as lithological criteria.

Within the area mapped (Fig. 2) the Problematicus Siltstone forms a conspicuous belt and, indeed, can be traced along the strike for tens of miles in Southland and South Otago. There is little doubt that the thick shell beds make up Trenchmann's bed f.

In only one reach of Otamita Stream is the section complete enough to allow the incoming of *M. problematicus* to be observed. This is the reach extending downstream from Gordon Stream junction. Here the lowest occurrence of the species is in thick shell beds (S169 806) 8 chains east of Gordon Stream. Siltstone with *Oretia* sp. preserved in pockets but never constituting shell beds (S169/805), of Oretian age underlies the Problematicus Siltstone and is a persistent formation within the area covered by the map (Fig. 2). Careful collecting is necessary to distinguish upper Oretian and lower Otamitan faunas for fragmentary valves, especially internal casts, of *Oretia* and *M. problematicus* cannot easily be distinguished.

The south-flowing tributary joining Otamita Stream at the north end of the S-bend cuts across the base of the Problematicus Siltstone at S169/822 where the following forms make up a shell bed:

Athyris cf. *wreyi* (Suess)
Spiriferina sp.
Halobia sp.
Mytilus problematicus Zittel
Mysidioptera sp.
?*Triaphorus* sp.
Grammatodon sp.

The limits of the formation are best exposed in this section which serves as the type section of the *problematicus* zone.

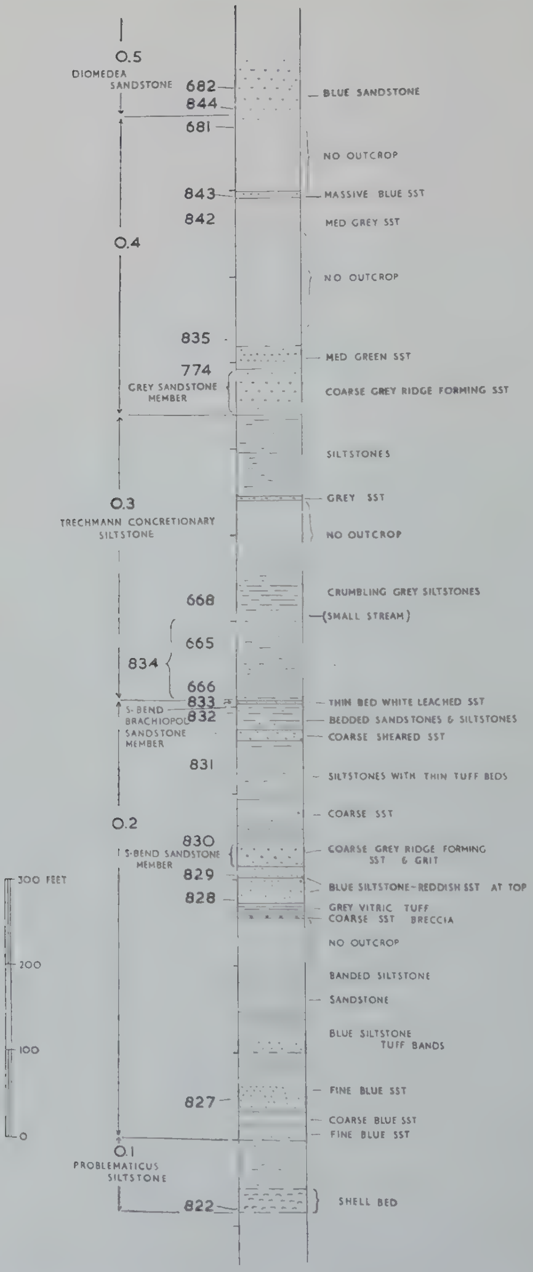

FIG. 5—Column showing lithology and formation thicknesses along the Otamitan type section shown in Fig. 4.

Formation 0.2: Sandstone with minor siltstone

About 500 ft of sandstone including coarse grained ridge-forming sandstone-grit and with minor siltstone and tuff forms a belt immediately north of Otamita Stream at the S-bend. It is covered by alluvium over much of the stream valley eastwards to Gordon Stream.

Fossiliferous sandstones (S169/827, *Athyris* cf. *wreyi* (Suess), *Retzia* sp.) pink, green and grey tuffaceous siltstones, and coarse sandstones succeed the Problematicus Siltstone in the type section and form a waterfall in a more westerly tributary. The coarse sandstones are probably to be correlated with the resistant members that form a conspicuous double buttress at the east end of the S-bend in Otamita Stream. A tuff, 10 ft thick, separates the coarse sandstone from further siltstone (S169/828) with:

Athyris cf. *wreyi* (Suess)
Spiriferina otamitensis Trech.
Halobia sp.

A distinctive siltstone with discontinuous stringers of pink sand (S169/829) succeeds and contains:

Athyris cf. *wreyi* (Suess)
Mentzelia n. sp.
Halobia sp.
Myophoria sp.

The *Mentzelia* is recorded above from Otamita Stream west of Dornoch Burn (S169/811) where it occurs in a horizon 100 ft above the top of the *problematicus* zone. It also occurs west of the Dornoch Burn Fault (S169/815) in siltstone exposed on the left bank of Otamita Stream in a strike reach where the following forms were collected from a horizon also about 100 ft above the top of the Problematicus Siltstone:

Athyris cf. *wreyi* (Suess)
Spiriferina otamitensis Trech.
Mentzelia n. sp.
Halobia sp.
Anodontophora angulata Trech.

S-bend Sandstone Member: Coarse-grained, unfossiliferous, grey sandstone-grit forms the main ridge immediately north of the north-flowing reach of the S-bend. It also forms a prominent rib in Otamita Stream south-east of this ridge.

The S-bend Sandstone is succeeded by 20 ft of siltstone (S169/830) with:

Spiriferina otamitensis Trech.
Halobia sp.
orthocone

A coarse-grained sandstone 25 ft thick separates this bed from a siltstone with weathered tuff bands and with *Mentzelia* n. sp. (S169/831). A further sandstone, light-weathering, locally sheared and 12 ft thick separates S169/831 from siltstone with decomposed tuff bands up to 2 ft thick with (S169/832):

Spiriferina otamitensis Trech.
Halobia sp.
Triaphorus zealandicus (Trech.)
Anodontophora sp.

S-bend Brachiopod Sandstone Member: About 4 ft thick, this micaceous brown fine-grained sandstone contains a brachiopod shell bed in its lowest 6–8 in. (S169/833) in which many small shells of *Athyris* cf. *wreyi* (Suess) are packed together along with *Halobia* sp., *Mentzelia* n. sp. and *Terebratula pachydentata* Trech.

This unit is distinctive in the type section but it has not been recognised with certainty elsewhere in Otamita Valley.

Formation 0.3: Trechmann Concretionary Siltstone

This formation consists of 330 ft of massive siltstone with siltstone concretions up to 2 in. in diameter and very minor sandstone. It is very well exposed to the west of the north-flowing reach of the S-bend where active screes are being undercut by the stream. Small fossils complete with shell may be readily picked out of the masses of chips of blue-grey siltstone (S169/834, 665, 666, 668, 584). The outcrop extends southwards, from a narrow ridge (S-bend brachiopod sandstone Member) with a solitary shrub growing on it, to a point about 230 ft south of the mouth of a small east-flowing tributary (Figs. 3, 4).

The section across the siltstone north of the stream mouth is well exposed and can be measured accurately. It is 108 ft thick and includes 20 thin but persistent decomposed tuff bands with an aggregate thickness of about 2 ft. Seven horizons of concretions were noted, some fossiliferous. These are generally locally cemented pockets with a nautiloid shell as nucleus; others are merely spheroids of siltstone.

The following forms occur in recently made collections (S169/834):

Rhynchonella sp.
Terebratula pachydentata Trech.
Spiriferina otamitensis Trech.
Athyris cf. *wreyi* (Suess)
A. manzavinioides (Trech.)
Nuculana semicrenulata (Trech.)
Paleoneilo otamitensis Trech.
Halobia sp.
Anodontophora angulata Trech.
Triaphorus zealandicus (Trech.)
Tutcheria parvula (Trech.)
Pleurotomaria hokonuiensis Trech.
P. hectori Trech.
Lepidotrochus marshalli (Trech.)
Proclydonautilus mandevillei (Marshall)
Cladiscites sp.

Trechmann (1918) recorded or described about 30 species of molluscs and brachiopods from bed c. Browne has marked the MS map referred to above at S169/834 as "main section of Trechmann." Many specimens of Trechmann's collecting are shelly and it is reasonably certain that he collected part of his bed c material from the Trechmann Concretionary Siltstone and at the site of S169/834. From bed c he recorded *T. pachydentata* and *A. wreyi* and all the pelecypods listed above, but in addition he found:

Macrodon sp.
Hokonuia limaeformis Trech.
Cassianella sp.
Pseudoplacunopsis placentoides Trech
Myophoria otamitensis Trech.
Paleocardita quadrata Trech.

Dentalium sp. was listed and a comparatively rich cephalopod fauna, namely: *Orthoceras* sp., *Conoceras trechmanni* (Kummel), arcestids and *Rhacophyllites* sp.

The disparity between lists based on recent collecting and Trechmann's list for bed c throws some doubt on the exact correlation of bed c and the locality S169/834. In the type section the higher part of the Trechmann Concretionary Siltstone to the south of the mouth of the small tributary stream is poorly exposed and is likely to have been so at the time Trechmann's collections were made. Recent collections may therefore be taken as representative of the faunule of the siltstone at the type section in Trechmann's time, and the differences in the two lists cannot be accounted for by present lack of exposure of the higher part of the section.

Some 55 chains downstream from S169/834 a clear section through 100 ft of beds (eroded by the stream on a north concave bend) exposes 78 ft of siltstone with very minor sandstone and about 16 bands of decomposed tuff. These are mostly less than 1 in. thick but occasionally may be up to 7 in. Concretions are not uncommon. There is a distinct faunule in a 17-in. bed of massive siltstone 26 ft above the lowest horizon exposed in the outcrop comprising (S169/849).

Halobia sp. and *Mentzelia* n. sp.

The succeeding 51 ft of siltstone which forms minor screes (S169/816) is richly fossiliferous and the following have been collected recently:

Rhynchonella sp.
Terebratula pachydentata Trech.
Spiriferina otamitensis Trech.
Athyris cf. *wreyi* (Suess)
A. manzaviniodes (Trech.)
Paleoneilo sp.
Halobia sp.
Cassianella sp.
Pseudoplacunopsis placentoides Trech.
Myophoria otamitensis Trech.
Dentalium sp.
Pleurotomaria hokonuiensis Trech.
Lepidotrochus marshallii (Trech.)
Orthoceras sp.
Proclydonautilus mandevillei (Marshall)

The siltstone is similar lithologically and faunally to Trechmann Concretionary Siltstone (although incidence of thin weathered tuff bands cannot be matched in detail). It is overlain by 21 ft of more finely bedded siltstone and sandstone with some richly fossiliferous layers that are often concretionary. The nature of these beds allows collection of certain larger forms such as *Hokonuia* that would be only rarely collected successfully in the more massive Trechmann Siltstone. The following have been collected recently (S169/671):

Terebratula pachydentata Trech.
Spiriferina otamitensis Trech.
S. cf. *trechmanni* (Wilckens)
Athyris cf. *wreyi* (Suess)
A. manzavinioides (Trech.)
Paleoneilo otamitensis Trech.
Myophoria otamitensis Trech.

Halobia sp.
Hokonuia limaeformis Trech.
Cassianella sp.
Anodontophora angulata Trech.
Triaphorus zealandicus Trech.
Pleurotomaria hokonuiensis Trech.
Proclydonautilus mandevillei (Marshall)
Arcestes sp.
Cladiscites sp.

With the exception of *Palaeocardita quadrata* and *Tutcheria parvula* all of Trechmann's bed c forms (the bed c fauna) are represented in the recent collections S169/671 and 816. If the S169/834 list is added, all forms of the bed c fauna are accounted for except *P. quadrata.* Thus the bed c fauna as distinct from bed c, a locality, has been re-collected.

Trechmann's bed e, overlying the Problematicus Siltstone and underlying bed c, was the horizon from which the holotypes of *Spiriferina otamitensis* Trech. and *Athyris manzavinioides* (Trech.) were collected. These forms are present in collections from S169/834, 816 and 671 and do not form a distinctive faunule along with Trechmann's other bed e forms: *Conularia* sp, and various forms of *Halobia.* Hence the location of Trechman's bed e is also uncertain but it is probably included in S169/834, 816 and 671 along with bed c.

Trechmann's bed b (20 ft of feldspathic sandstone interbedded with shaly bands with "*Nautili, Arcestes, Discophyllites, Halobia hochstetteri,* etc.") may be equivalent to S169/671 where cephalopods are not uncommon. These fossils are, however, more conspicuous in a locality about 100 chains east of the S-bend (referred to above, p. 650) as the site of Marshall's cephalod collection (S169/801).

About 23 ft of siltstone with some rusty concretionary bands and minor sandstone (S169/850) is succeeded by 4 ft of siltstone with conspicuous nautiloids (S169/801) the latter siltstone forms a re-entrant on the hill surface and is overlain by resistant plant-bearing sandstone. S169/850 and 801 have yielded the following (in recent collections):

Rhynchonella sp.
Terebratula pachydentata Trech.
Spiriferina otamitensis Trech.
Athyris manzavinioides (Trech.)
Halobia sp.
Myophoria otamitensis Trech.
Mytilus sp.
Anodontophora angulata Trech.
Pleurotomaria hectori Trech.
P. hokonuiensis Trech.
Proclydonautilus mandevillei (Marshall)
ammonites

Correlation of S169/850, 801 with the type section cannot be established by plotting the outcrop on aerial photographs but there is close lithological and faunal similarity to S169/671 which in turn is interpreted as equivalent to the Trechmann Siltstone.

Formation 0.4: Sandstone including plant-bearing sandstone and minor siltstone

Poorly exposed sandstone and minor siltstone forms the higher ground west of the north-flowing reach of the S-bend and makes up the uppermost 400 ft of the Otamitan Stage.

Grey Sandstone Member: A prominent coarse massive grey sandstone here termed Grey Sandstone Member, overlies the Trechmann Siltstone. It dips 80°S. and forms bars in the stream bed and can be followed on aerial photos for many chains along the strike, thereby helping to establish correlation of the Trechmann Siltstone and rocks further east (S169/816).

The basal member is succeeded by siltstone, poorly exposed in the type section (S169/774, 835) with:

Terebratula pachydentata Trech.
Mentzelia sp.
Halobia sp.
Anodontophora angulata Trech.

This is overlain by coarse grained brown-weathering plant-bearing sandstone. Pockets with numerous fragments of *Halobia* sp. (S169/842) occur in the sandstone along with nautiloids and other poorly preserved fossils.

At least 50 ft of compact blue massive sandstone with carbonaceous fragments succeeds to the south and in a prolonged search (S169/843) one specimen of *Halobia* sp. was seen and a small rhynchonellid collected. The sandstone forms a prominent bar in Otamita Stream.

Fossils are present in most of the Otamitan beds overlying the Trechmann Siltstone in the type section but exposure is indifferent and it is unlikely that Trechmann collected extensively here.

Formation 0.5: Diomedea Sandstone

The uppermost sandstone of Formation 0.4 is succeeded by a slightly finer grained greenish-grey massive plant-bearing sandstone which forms an extensive platform-like bar in the stream. Fossils are not uncommon (S169/844) and constitute one species:

Rastelligera diomedea (Trech.)

Diomedea Sandstone crops out 2 chains to the east of the stream (S169/682) on a tussock-covered slope; sandstone with *Halobia* sp. (S169/681) 30 ft lower stratigraphically crops out to the north on the same slope.

The entry of *R. diomedea* is taken to mark the onset of post-Otamitan time. The key fossil of the Warepan Stage (*Monotis richmondiana* Zittel) is not present at Otamita, and the Diomedea Sandstone is unlikely to be Warepan in age. Upstream from the S-bend, beyond the mouth of Peel Stream the Diomedea Sandstone is immediately underlain by a distinctive breccia (S169/799, 825) with *Halobia* sp. in highly calcareous cobbles and in the matrix a faunule including polyzoans, echinoids (spines) and brachiopods. The latter are reminiscent of Warepan and basal Otapirian forms and lend support to the view that the breccia is a slump deposit occupying a position along the strike between the Diomedea Sandstone and Formation 0·4. Warepan beds including those with *Monotis richmondiana* occupy the position of the breccia in many sections in New Zealand.

FAUNAL INDEX

The following have been described from Otamitan localities in Otamita Valley:

Terebratula pachydentata C. T. Trechmann, 1918
Spiriferina otamitensis C. T. Trechmann, 1918
Athyris manzavinioides (C. T. Trechmann, 1918)
Nuculana semicrenulata (C. T. Trechmann, 1918)
Paleoneilo otamitensis C. T. Trechmann, 1918
Myophoria otamitensis C. T. Trechmann, 1918
Halobia zealandica C. T. Trechmann, 1918
Hokonuia limaeformis C. T. Trechmann, 1918
H. rotundata C. T. Trechmann, 1918
Pseudoplacunopsis placentoides C. T. Trechmann, 1918
Anodontophora angulata C. T. Trechmann, 1918
A. ovalis C. T. Trechmann, 1918
A. edmondiiformis C. T. Trechmann, 1918
Triaphorus zealandicus (C. T. Trechmann, 1918)
Tutcheria parvula (C. T. Trechmann, 1918)
Pleurotomaria hokonuiensis C. T. Trechmann, 1918
P. (Sisenna) hectori C. T. Trechmann, 1918
Lepidotrochus marshalli (C. T. Trechmann, 1918)
Cenoceras trechmanni (B. Kummel, 1953)
Proclydonautilus mandevillei (P. Marshall, 1909)
Arcestes hokonui P. Marshall, 1909

The following have been described from Otamitan horizons away from Otamita Valley:

Spiriferina (Rastelligera) acutissima C. T. Trechmann, 1918
Myophoria heslingtonensis C. T. Trechmann, 1918
Mytilus problematicus K. Zittel, 1864.
M. mirabilis C. T. Trechmann, 1918
Palaeocardita quadrata C. T. Trechmann, 1918
Atlantobellerophon zealandicus C. T. Trechmann, 1930

The following have been described from localities that may be Otamitan:

Athyris wreyi (E. Suess, 1864)
Cardiomorpha? nuggetensis C. T. Trechmann, 1918
Paleoneilo hamiltoni O. Wilckens, 1927
P. mundeni C. A. Fleming, 1954
Halobia hochstetteri E. von Mojsisovics, 1864
Hokonuia parki O. Wilckens, 1927

Hypotypes of the following species, figured by C. T. Trechmann (1918), were collected from Otamitan horizons:

Conularia sp.
Halorella sp.
Terebratula cf. hungarica A. Bittner, 1890
Paleoneilo cf. *praeacuta* A. von Klipstein, 1845
Macrodon cf. *curionii* A. Bittner, 1895
Cassianella sp.
Chlamys sp.
Dentalium sp.
Orthoceras sp.
Cladiscites sp.
Pinacoceras sp.
Rhacophyllites sp.
Arcestes sp.

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CORRIGENDA

N.Z. Geol. Geophysics 3 (3)

Particle size reduction of clay minerals by freezing and thawing *by I. C. McDowall*

p. 339, Fig. 1; (b) *should read* (c)
(c) *should read* (e)
(d) *should read* (b)
(e) *should read* (d)

Sea level fluctuations during the last 4,000 years as recorded by Chenier Plain, Firth of Thames, New Zealand *by J. C. Schofield*

p. 471, Fig. 3: (e) *should read* (c)

p. 476, Table 1:

Ridge (5) Accepted Sea Level *should be* + 0·5 ft

Ridge (6) Accepted Sea Level *should be* 0·0 ft

The Jurassic Age of some supposedly Triassic Mollusca described by Wilckens (1927) from Mt St Mary *by I. G. Speden*

p. 513, line 31:

Haastina haastiana Wilckens *should read Haastina haastiana* (Wilckens)

p. 514, line 4:

Hastina haastiana Wilckens *should read Haastina haastiana* (Wilckens)

p. 519, lines 21 and 24:

Patella nelsonensis Marwick *should read Patella nelsonensis* Trechmann

p. 520:

Athyris Kaihikuana (Trechmann) *should be* included in the list under 1 (a) (i) and *Spiriferina* cf *parki* Wilckens in 1 (a) (ii)

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